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Dean et al.

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(54) **HONEYCOMB STRUCTURE**

(56) **References Cited**

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U.S. PATENT DOCUMENTS

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2,704,587 A	3/1955	Pajak	
3,086,624 A	4/1963	Wyatt	
3,196,533 A	7/1965	Ida et al.	
3,212,189 A *	10/1965	Savit	33/1 CC
3,460,233 A	8/1969	Pfaffenberger et al.	
3,616,141 A	10/1971	Anderson	
4,076,880 A *	2/1978	Geschwender	428/116
4,273,836 A	6/1981	Campbell et al.	
4,411,381 A	10/1983	Ittner et al.	

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 269 days.

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(Continued)

FOREIGN PATENT DOCUMENTS

(21) Appl. No.: **13/588,826**

EP	0474161 A2	3/1992
GB	2117679 A	10/1983

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OTHER PUBLICATIONS

Rieger: "Krone Basteln," Kinderspiele-Welt.de, May 2010, 4 pages, accessed Jul. 1, 2013, <http://www.kinderspiele-welt.de/basteln-und-werkeln/krone-basteln.html> (English translation, 4 pages, accessed Jul. 19, 2013).

(Continued)

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B29D 24/00	(2006.01)
B29D 99/00	(2010.01)

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(52) **U.S. Cl.**

CPC . **B32B 3/12** (2013.01); **B21D 47/00** (2013.01); **B29D 24/005** (2013.01); **B29D 99/0089** (2013.01); **Y10T 156/1036** (2015.01); **Y10T 428/24149** (2015.01)

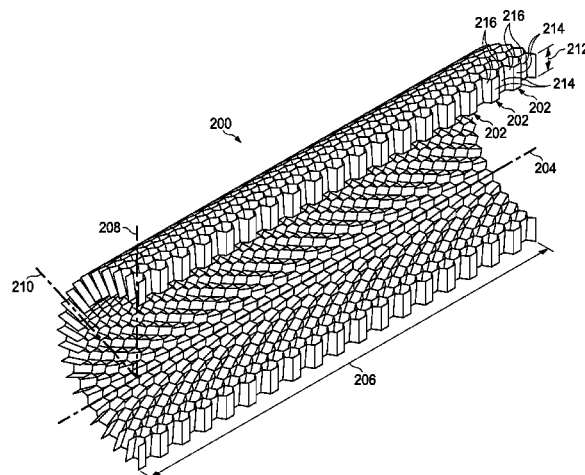
(57) **ABSTRACT**

A method and apparatus for forming a ribbon configured for use in forming a honeycomb structure when the ribbon is in a folded state. The ribbon comprises a first edge and a second edge. At least one portion of the first edge is not parallel to at least one portion of the second edge when the ribbon is in an unfolded state.

(58) **Field of Classification Search**

CPC B32B 3/12
USPC 428/116, 118
See application file for complete search history.

20 Claims, 16 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

4,457,963	A	7/1984	Ittner et al.	
4,548,665	A	10/1985	Morin	
4,981,744	A	1/1991	Swank	
5,024,369	A	6/1991	Froes et al.	
5,064,493	A	11/1991	Smith, II	
5,126,183	A	6/1992	Smith, II	
5,150,507	A	9/1992	Goela et al.	
5,270,095	A	12/1993	Ito et al.	
6,372,322	B1	4/2002	Devaguptapu	
8,481,143	B2	7/2013	Dean et al.	
2008/0145602	A1 *	6/2008	Hendren et al.	428/116

FOREIGN PATENT DOCUMENTS

JP	58025531	A	2/1983
WO	WO2008094743	A2	8/2008

OTHER PUBLICATIONS

EP search report dated May 28, 2013 regarding application 12181293.7-1706/2581215, reference NAM/P124234EP00, applicant The Boeing Company, 10 pages.

EP search report dated Mar. 18, 2013 regarding application 12181293.7, reference NAM/P124234EP00, applicant The Boeing Company, 6 pages.

Notice of allowance dated Apr. 19, 2013 regarding U.S. Appl. No. 12/214,848, 13 pages.

Dean et al., "Thick Curved Honeycomb Core With Minimal Forming," U.S. Appl. No. 13/214,848, filed Aug. 22, 2011, 41 pages.

Non-final office action dated Jan. 2, 2013 regarding U.S. Appl. No. 13/214,848, 8 pages.

Non-final office action dated Oct. 11, 2012 regarding U.S. Appl. No. 13/214,848, 15 pages.

* cited by examiner

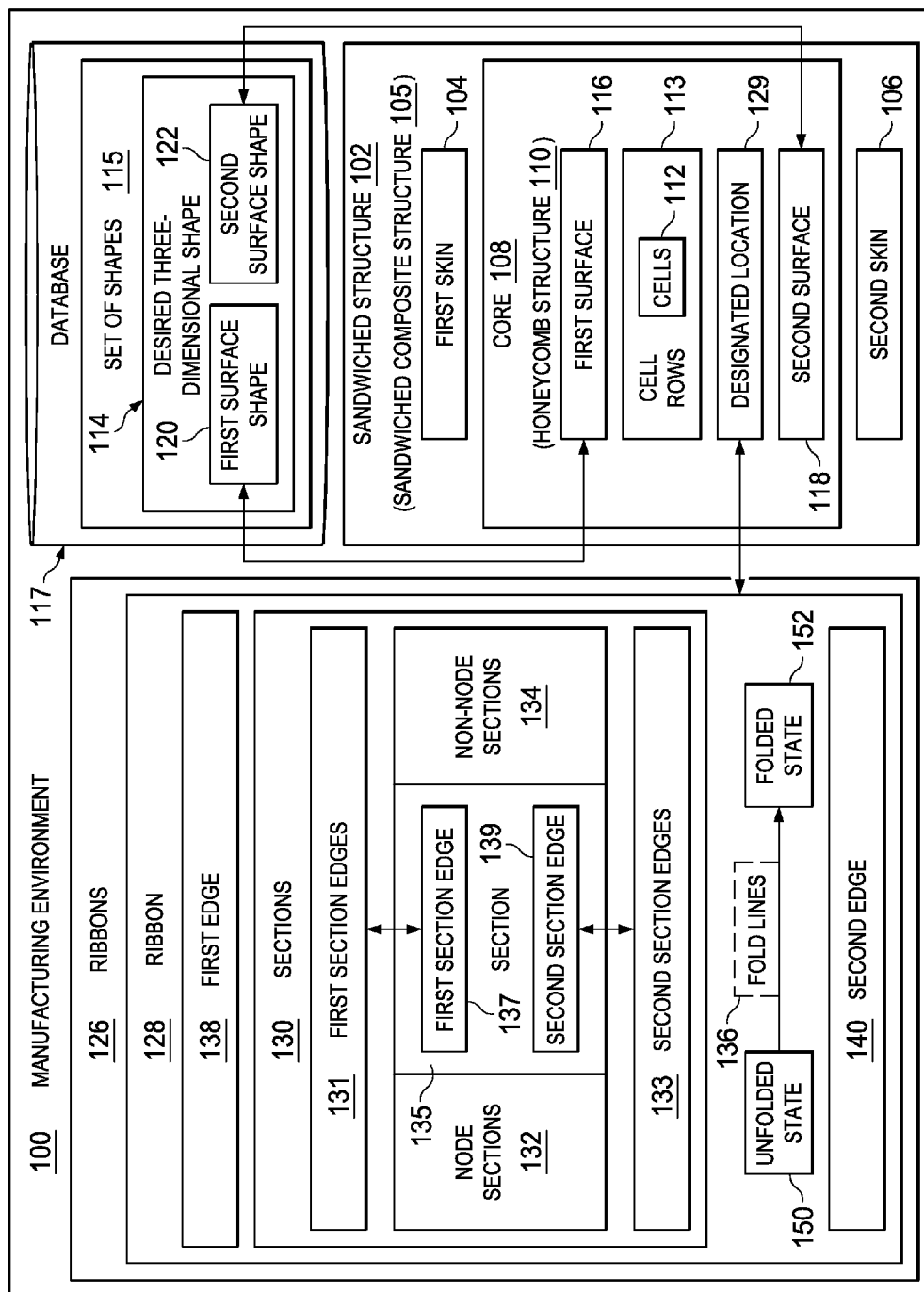
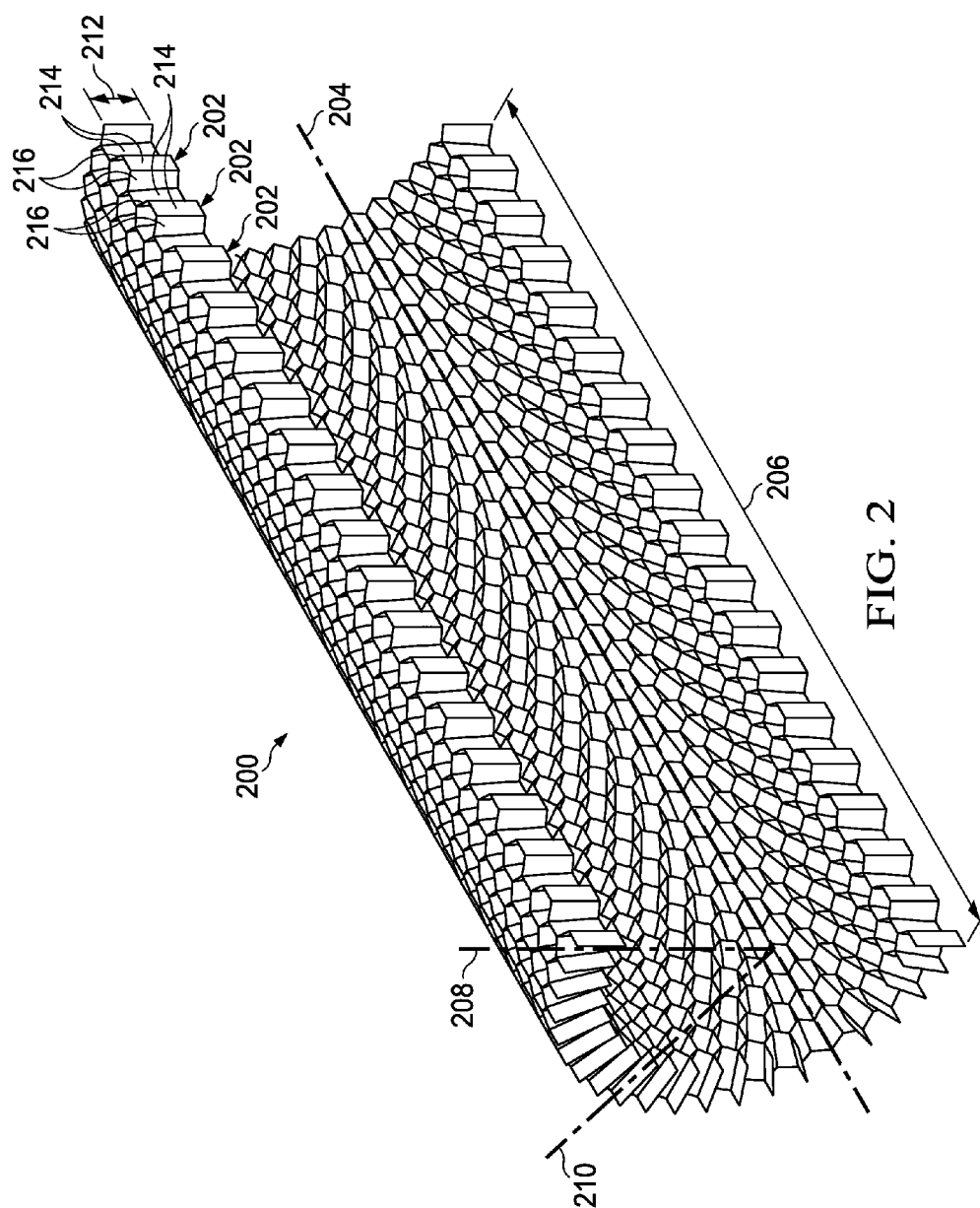


FIG. 1



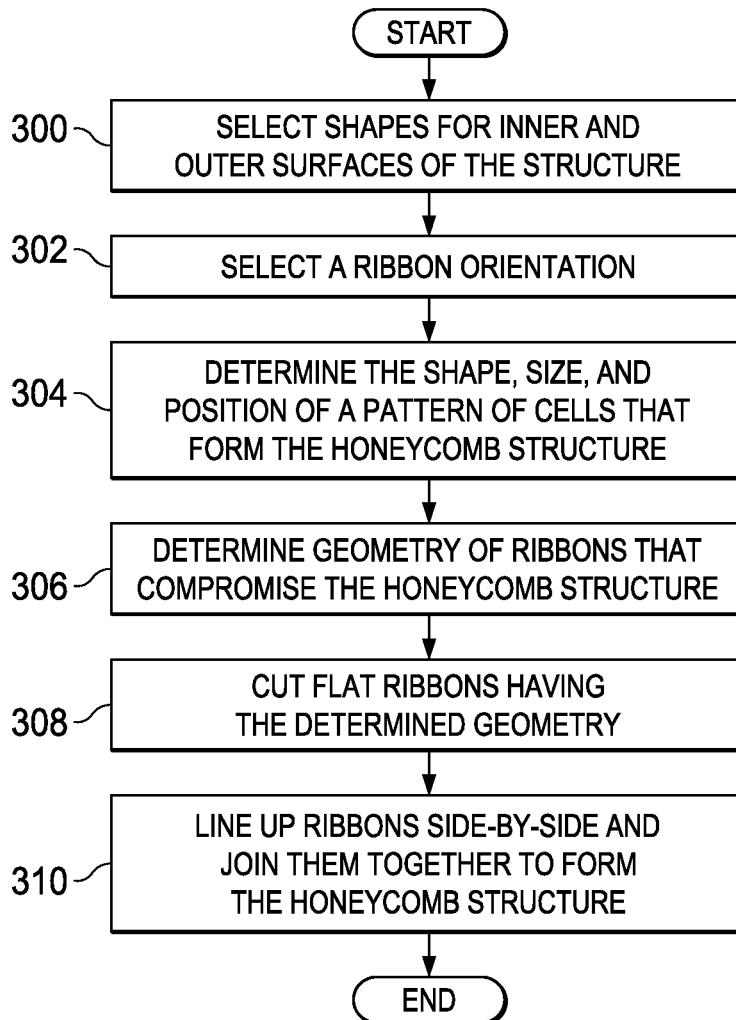
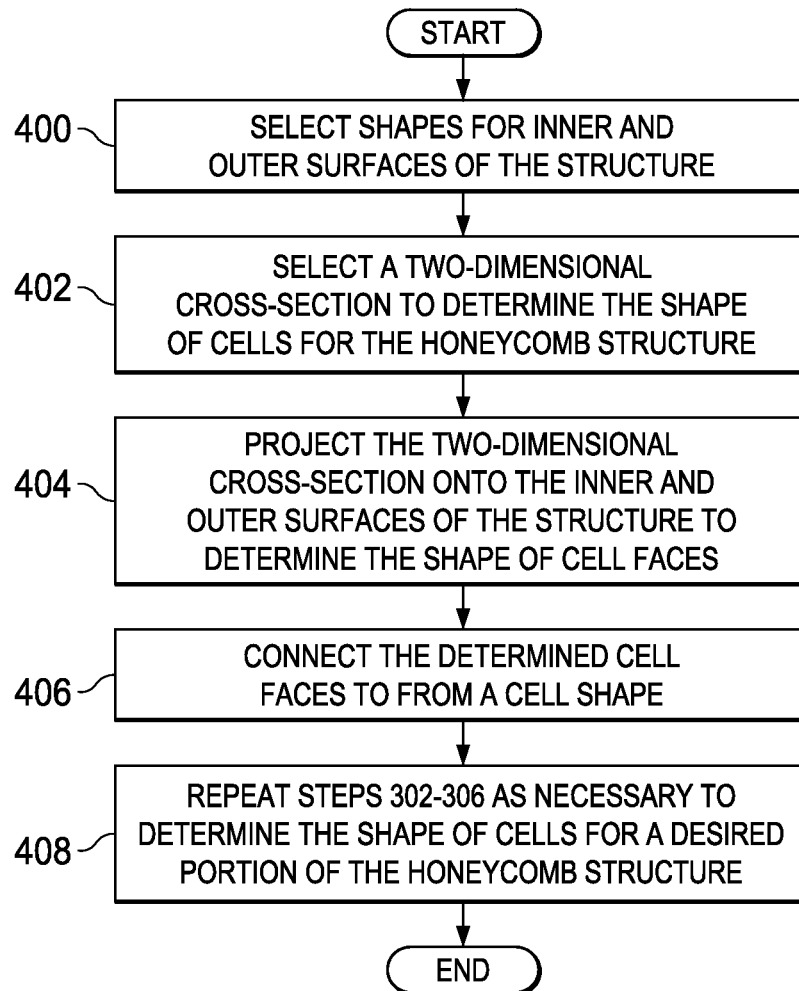
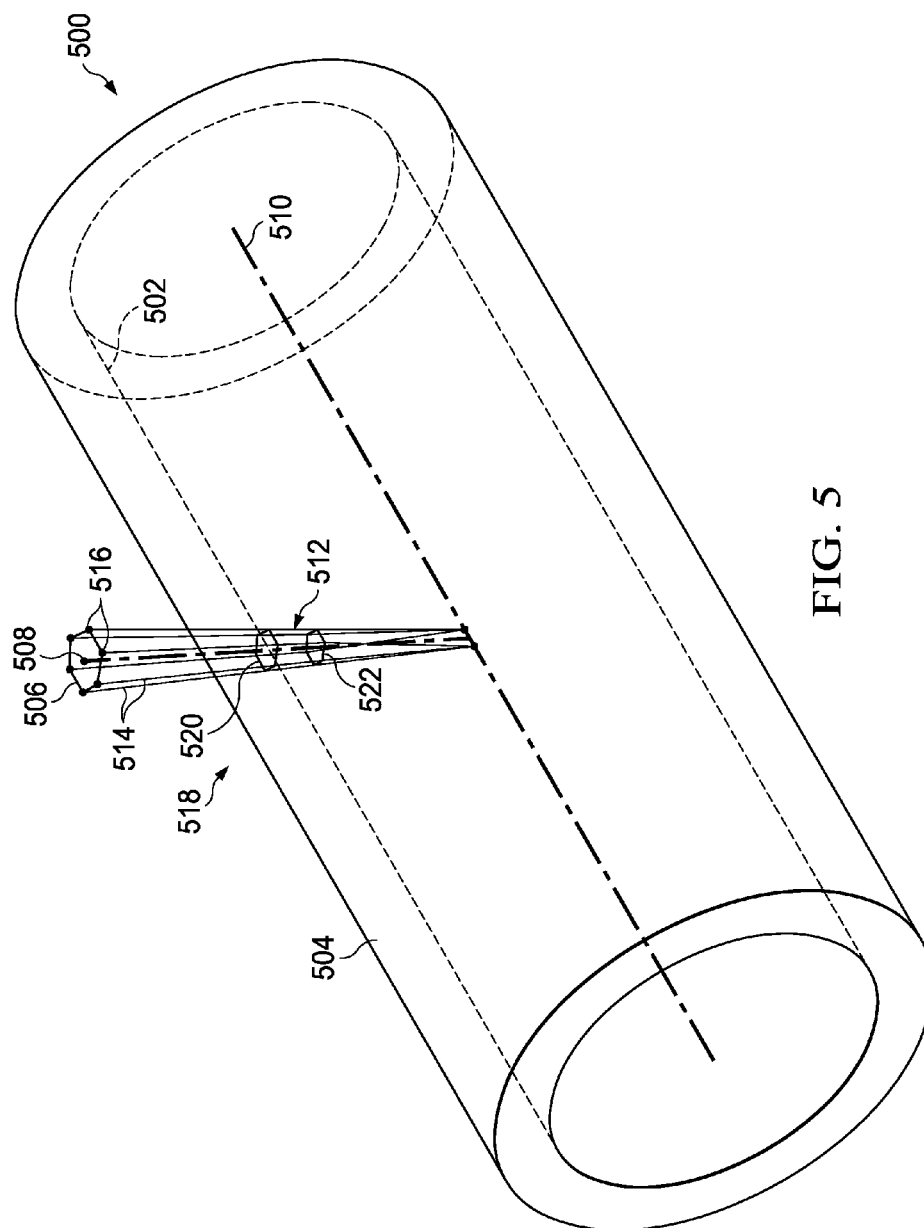


FIG. 3

**FIG. 4**



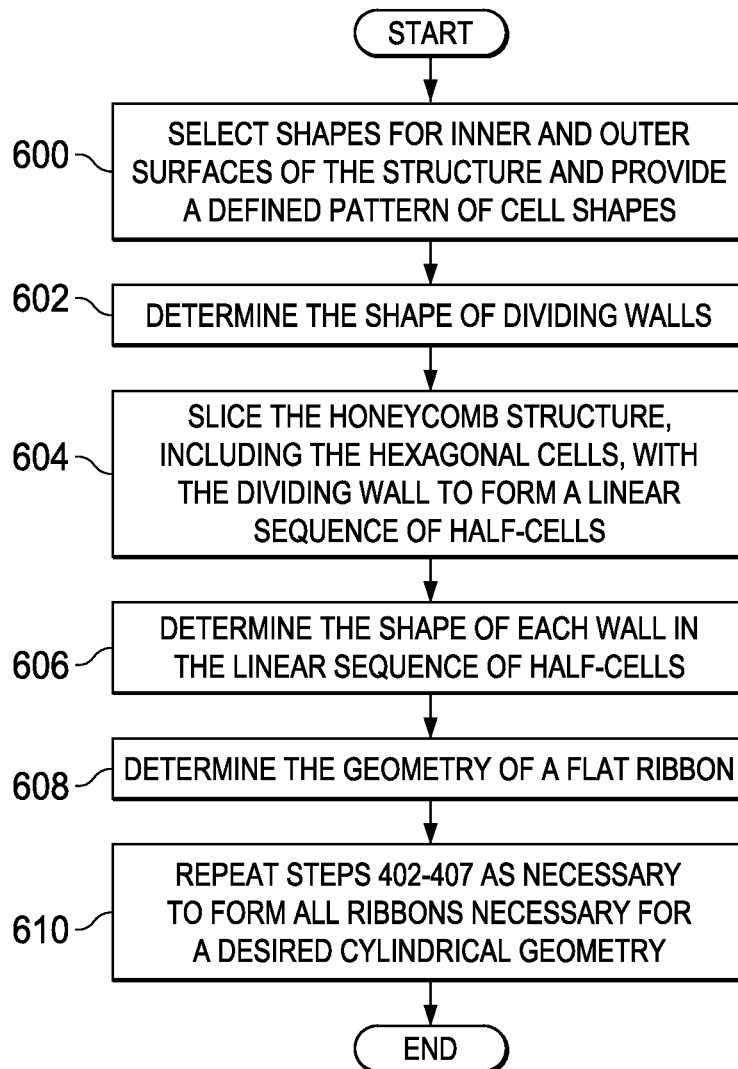


FIG. 6

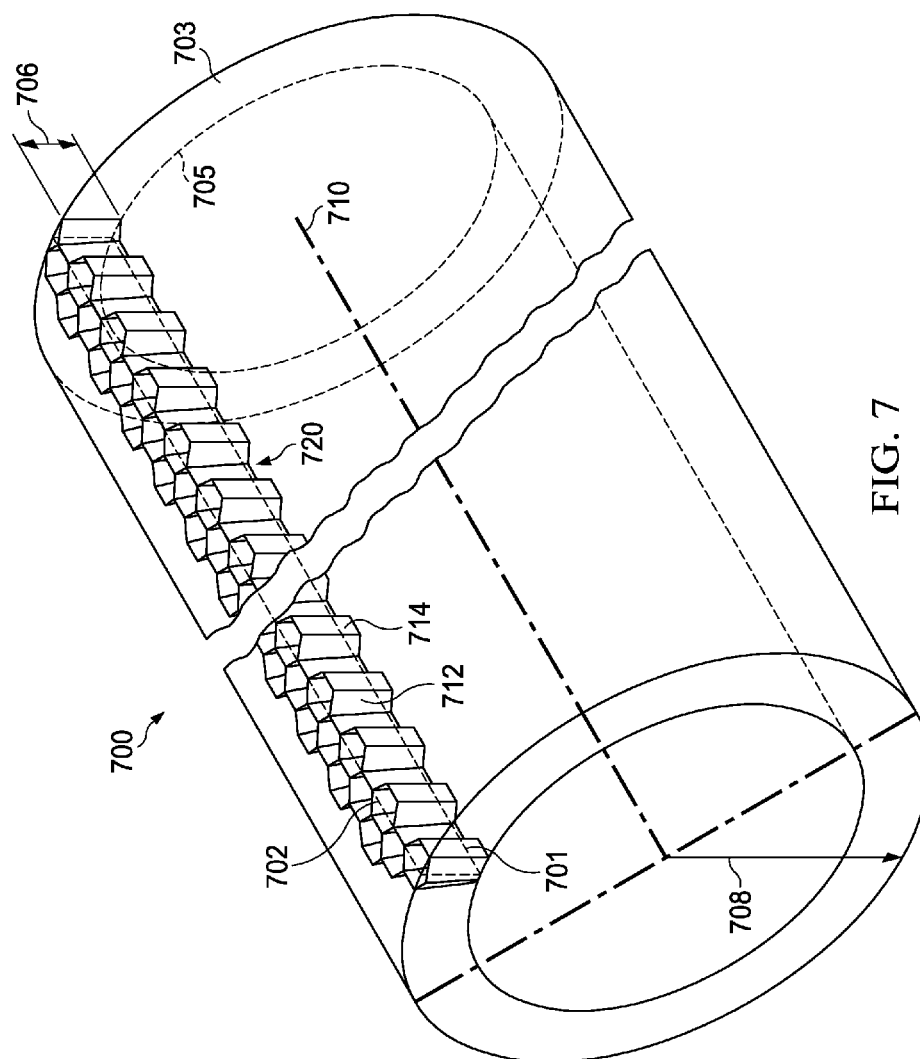


FIG. 7

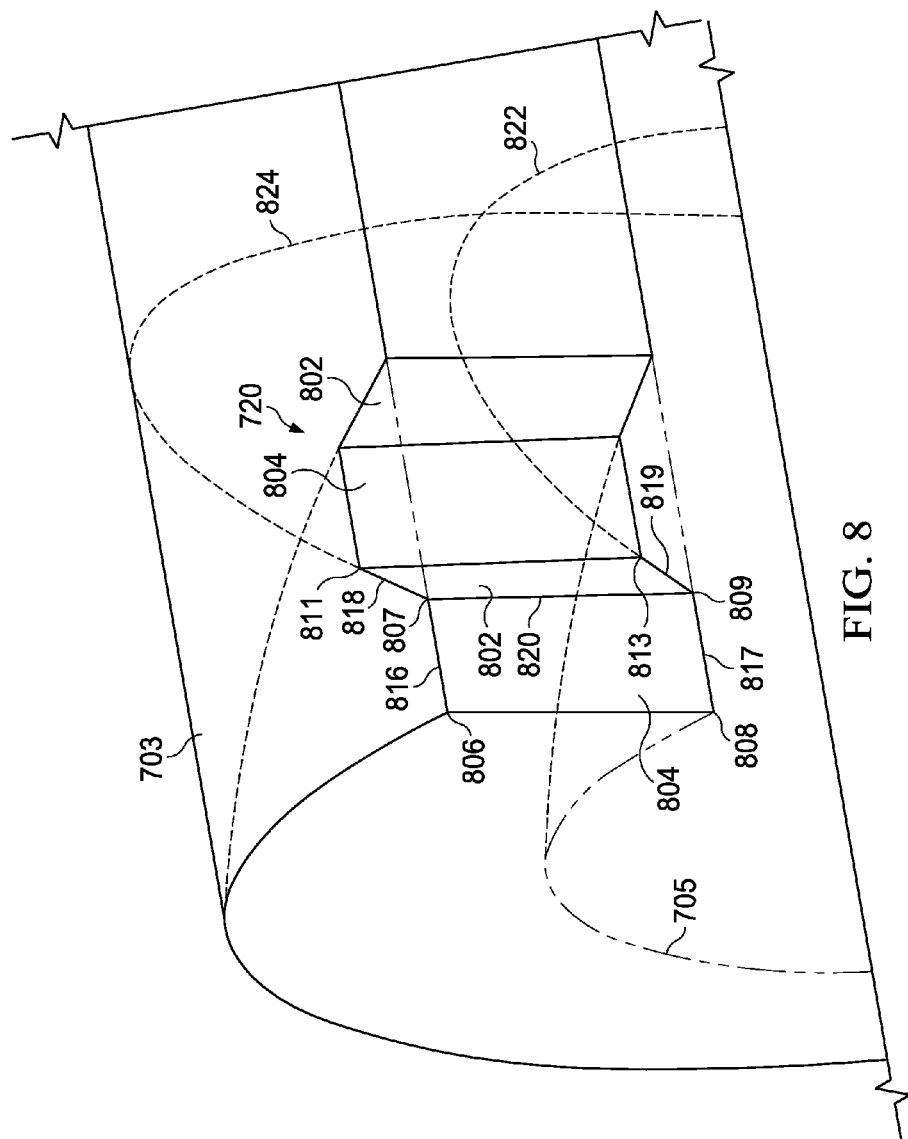


FIG. 8

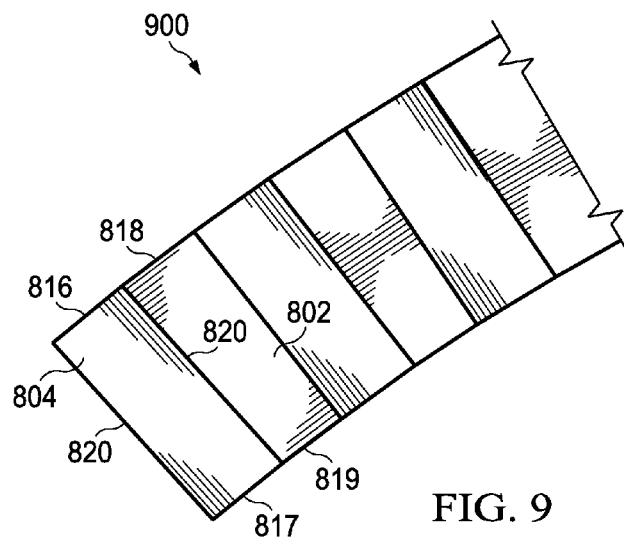


FIG. 9

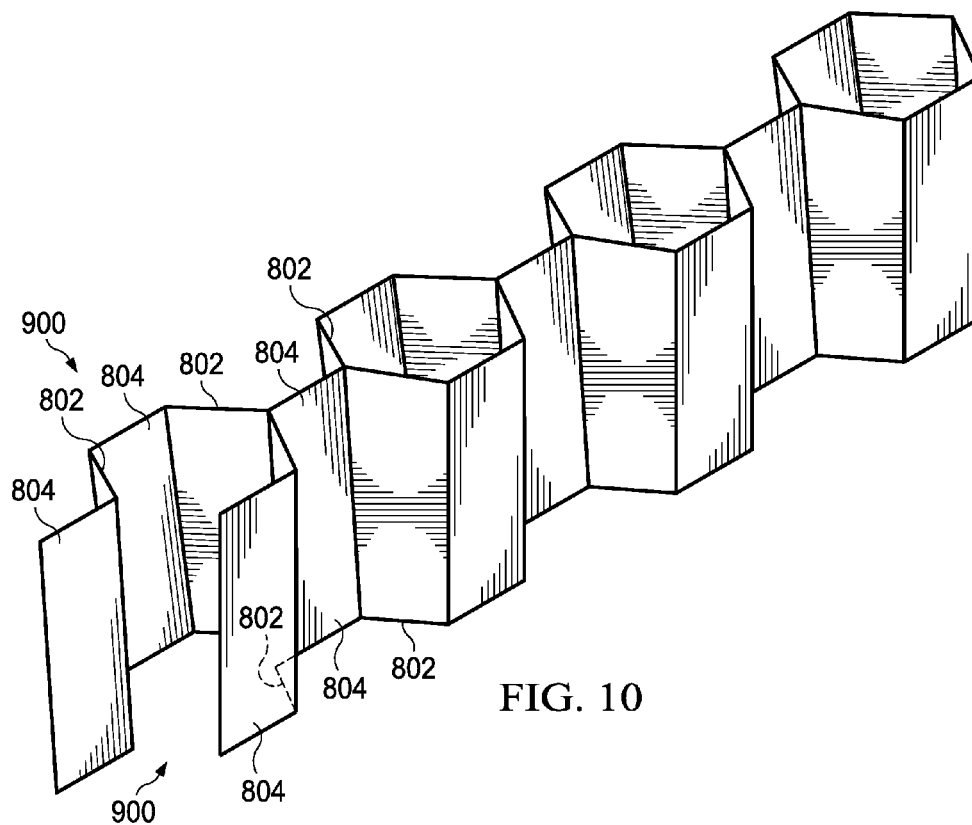


FIG. 10

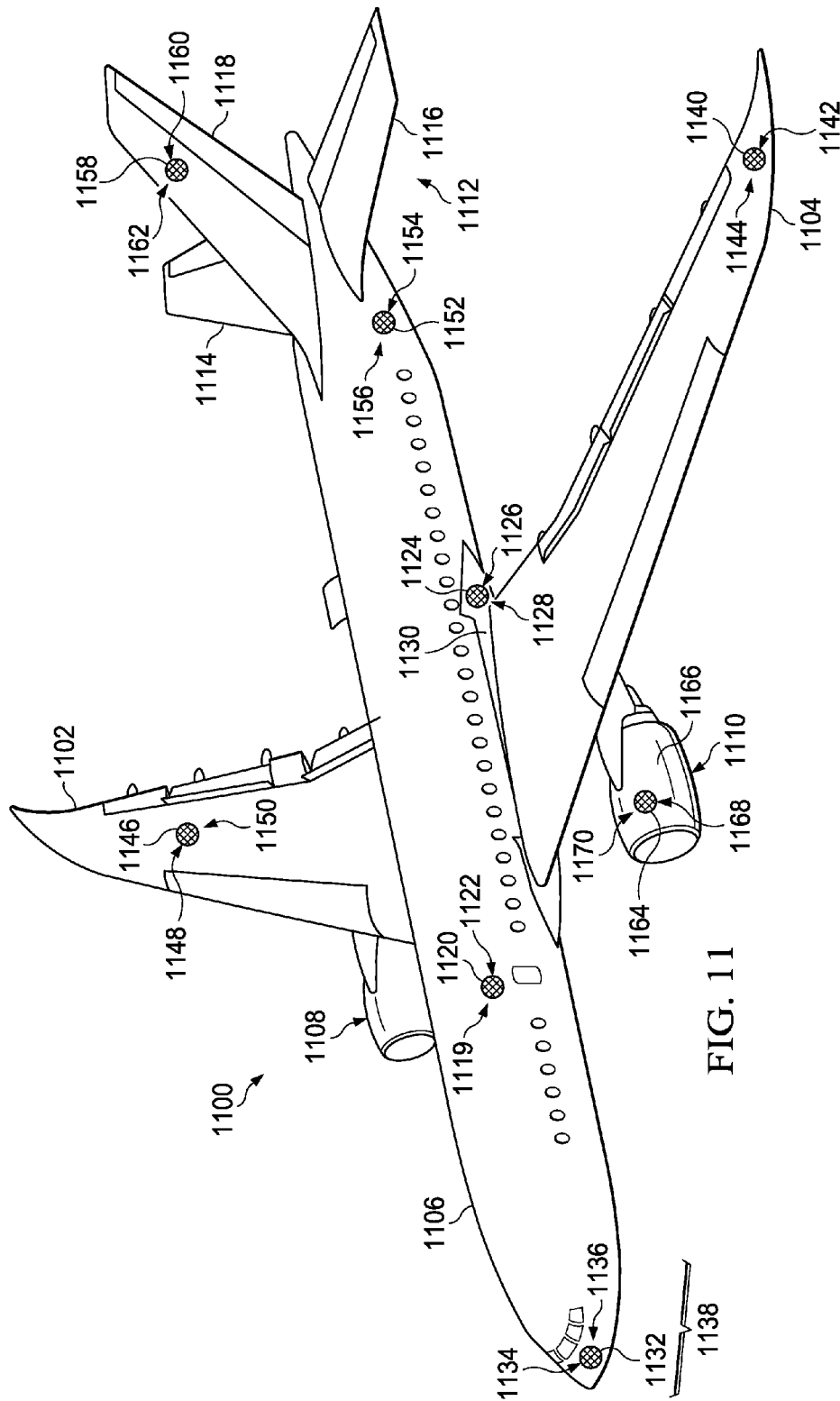


FIG. 11

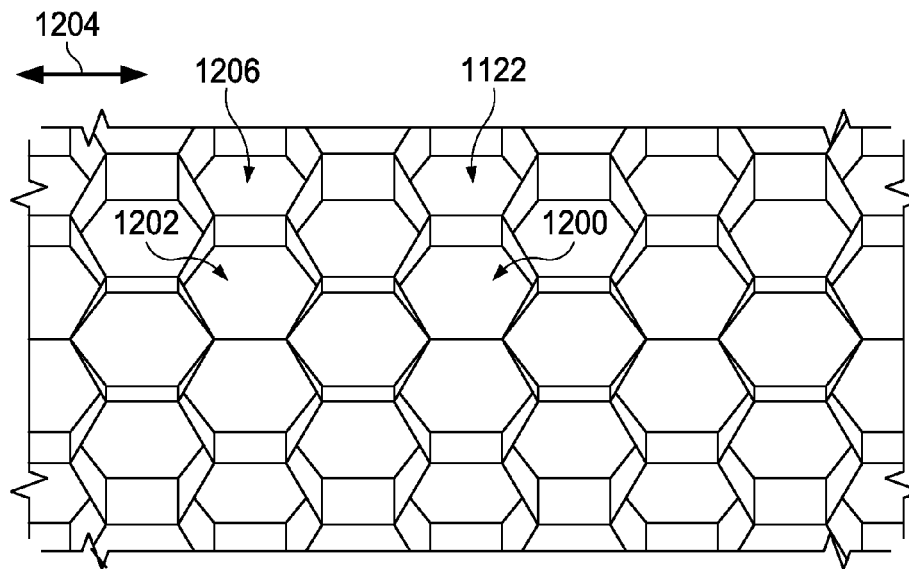


FIG. 12

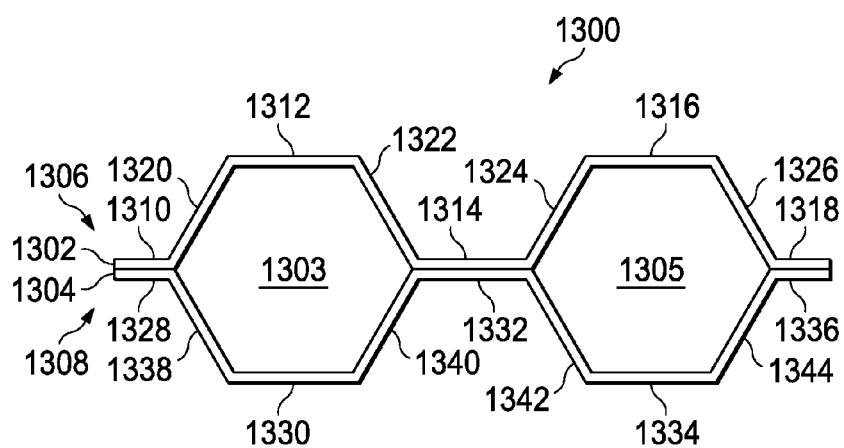
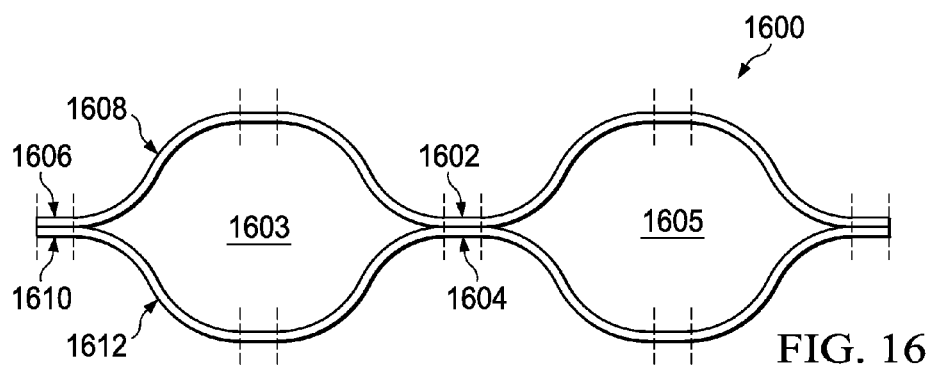
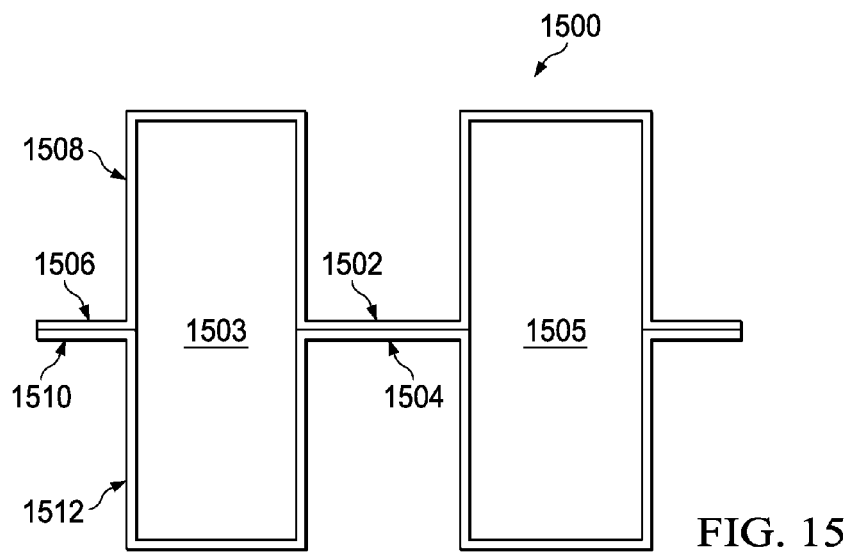
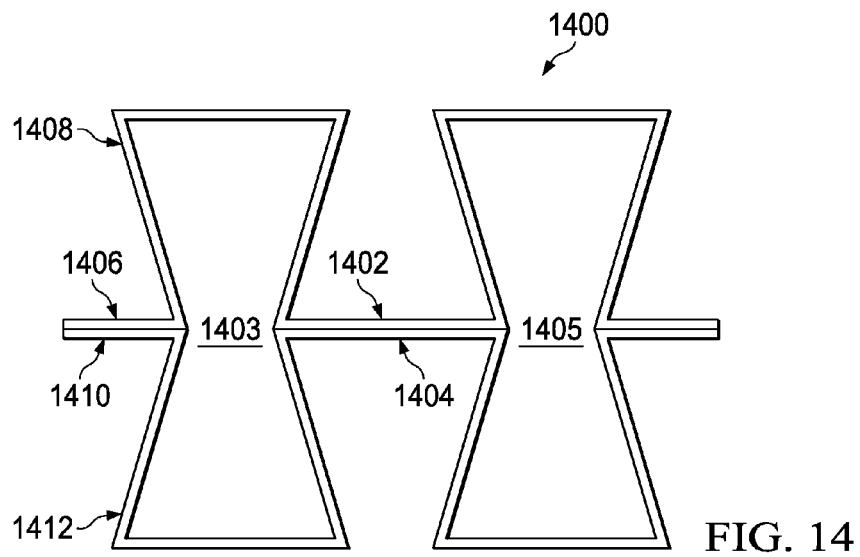


FIG. 13



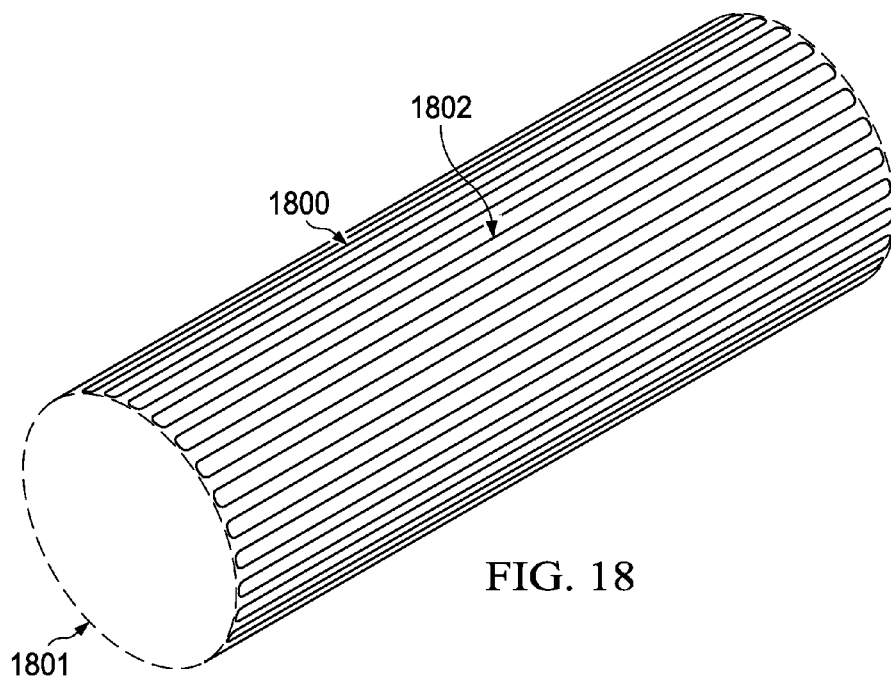
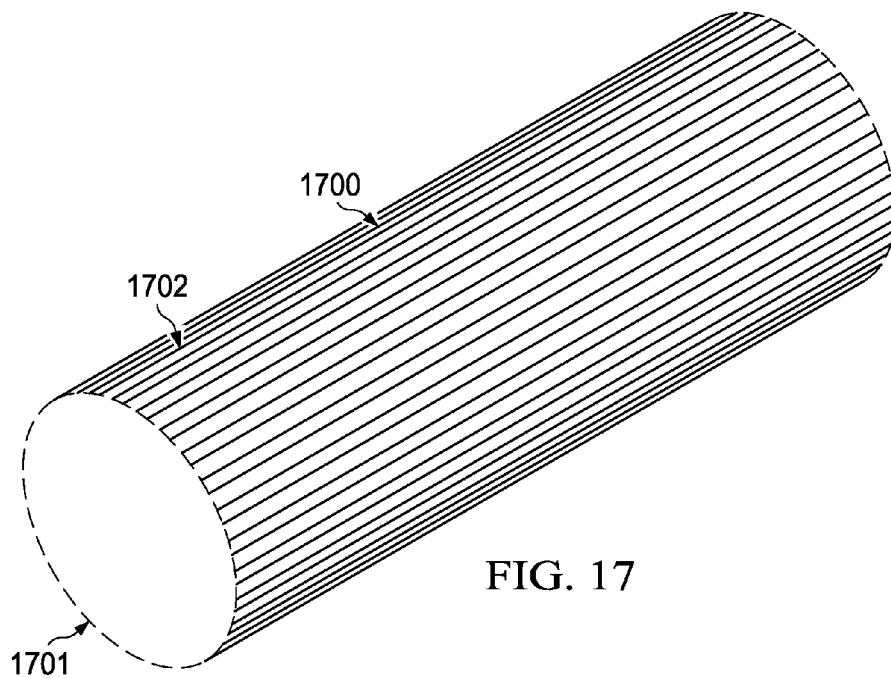


FIG. 19A

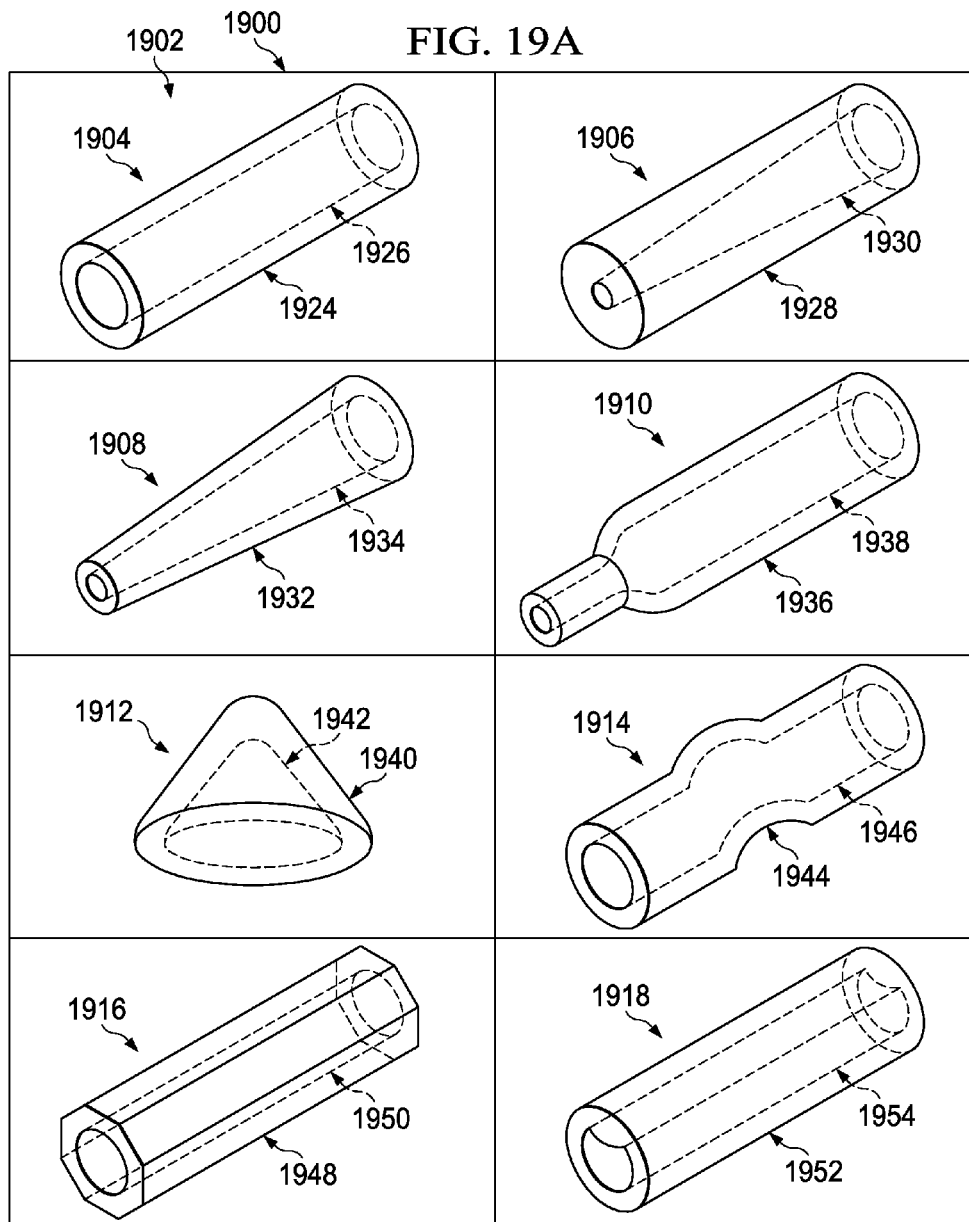
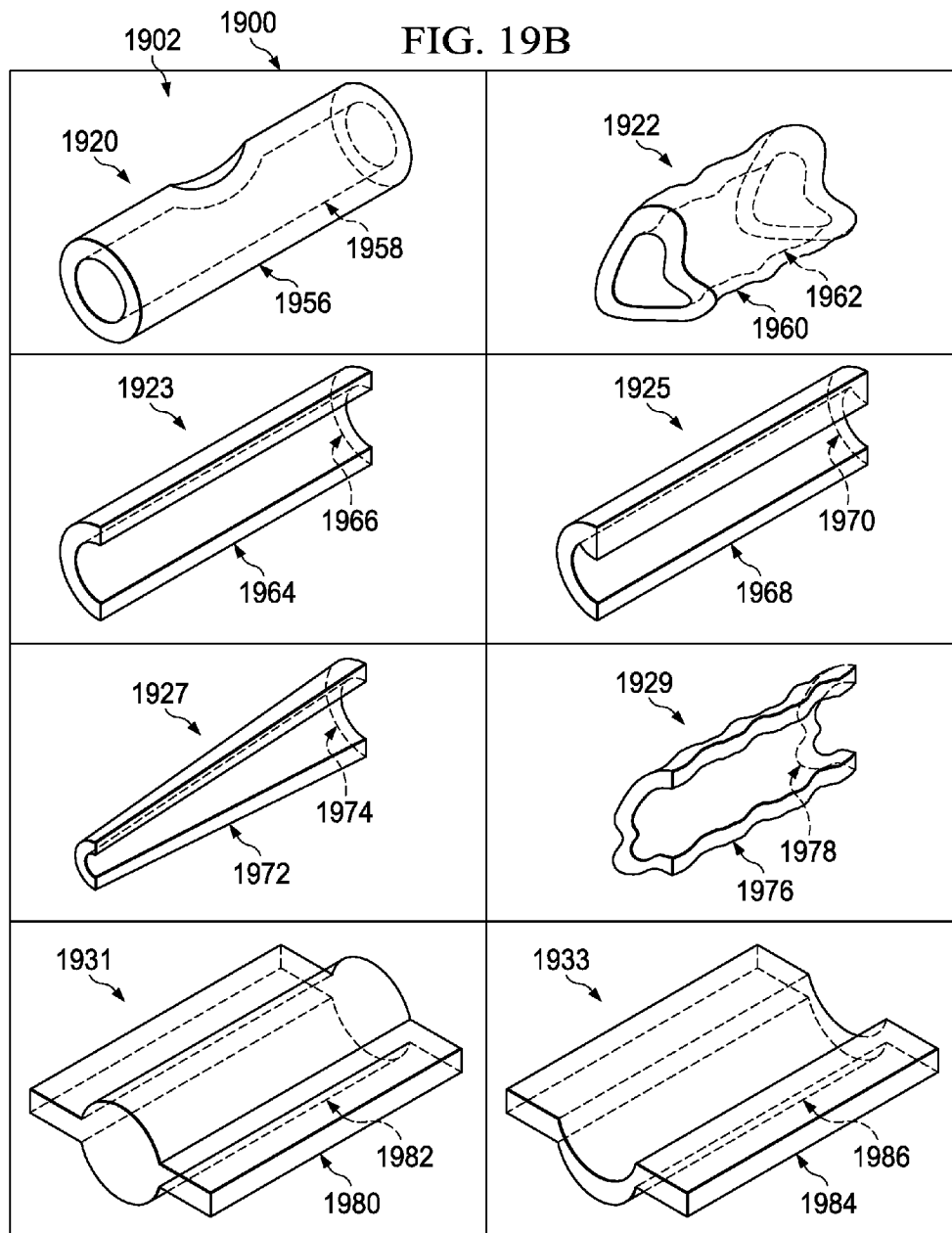


FIG. 19B



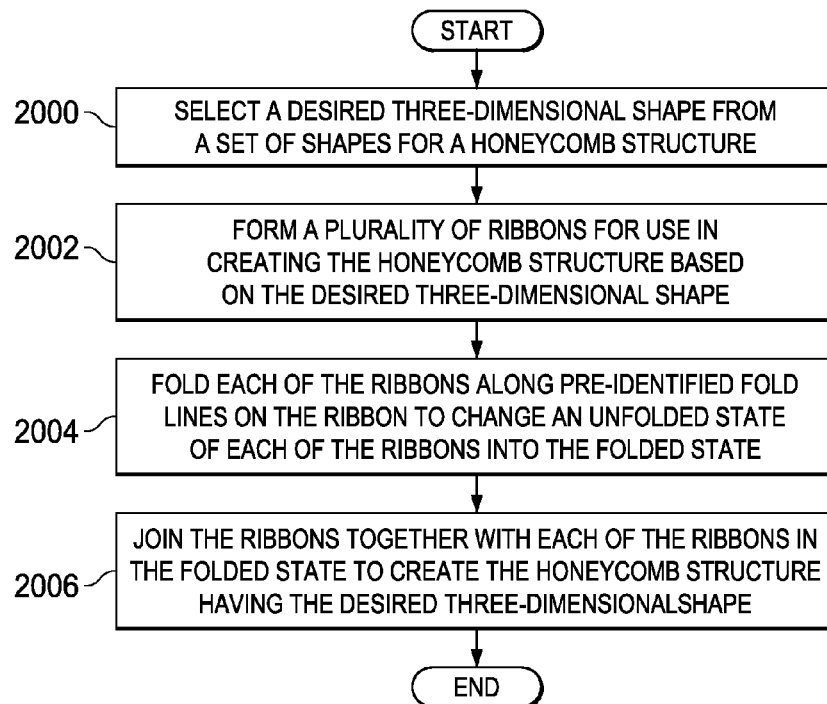


FIG. 20

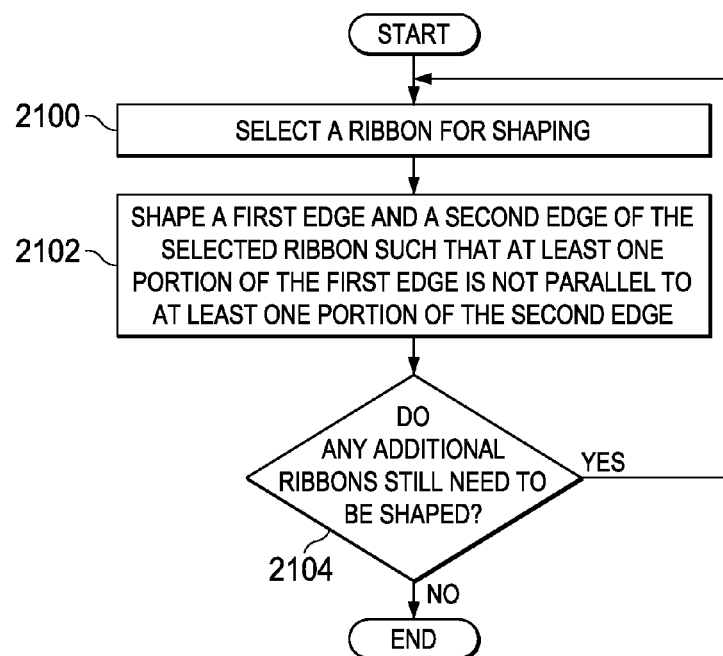


FIG. 21

1

HONEYCOMB STRUCTURE**CROSS-REFERENCE TO RELATED APPLICATION**

This application is a continuation-in-part of U.S. patent application Ser. No. 13/214,848, filed on Aug. 22, 2011, now U.S. Pat. No. 8,481,143, issued Jul. 9, 2013, entitled "Thick Curved Honeycomb Core with Minimal Forming", which is incorporated herein by reference.

BACKGROUND INFORMATION**1. Field**

This disclosure relates generally to cellular structures and, in particular, cellular structures having non-planar shapes. Still more particularly, the present disclosure relates to a method and apparatus for forming a cellular structure using ribbons configured to be folded and joined such that the cellular structure has a three-dimensional (3D) shape.

2. Background

A honeycomb structure, also referred to herein as a "honeycomb core," a "core material," or simply a "core," typically comprises a plurality of abutting rectangular or hexagonal cells shaped to a desired form. Honeycomb structures are often used as structural support for their high strength to weight ratio due to the low density of the honeycomb formation.

Honeycomb structures are typically manufactured from a thin, flat base material such as metal or paper. The flat base material is cut into narrow, elongated strips or ribbons, which are folded or bent into contoured strips of semi-hexagonal peaks and troughs. For example, an elongated strip of a material may be scored at regularly spaced intervals. To form regular hexagonally shaped cells, the score lines would be parallel to the ends of the strip and the material would be folded along the score lines to an angle of about 60°, twice in one direction, then twice in the opposite direction, and continuously alternating in that fashion.

The resulting folded strips are then joined together using adhesive, spot welding techniques, brazing techniques, and/or other known joining methods to form a structure having a series of hexagonally shaped cells, thereby forming a flat or substantially planar honeycomb structure. Although cells in a honeycomb structure are typically hexagonal, honeycomb structures may also be formed from cells having non-hexagonal shapes.

The resulting honeycomb structure, which consists of a substantially planar structure having cells with walls oriented in a direction perpendicular to the flat surface of the structure, may be able to sustain large loads in a direction parallel to the walls of the honeycomb cells, while also being lightweight due to an absence of material within the cells.

In many applications, it may be desirable to form a honeycomb structure that is non-planar. Various methodologies and apparatuses have been developed for shaping honeycomb structures into particular non-planar shapes.

For example, without limitation, some currently available methods for forming curved honeycomb structures begin with a pre-formed flat honeycomb structure and then mold or form this flat honeycomb structure into a desired shape that is non-planar.

As one illustrative example, one method of producing a contour consisting of short angle bends in a honeycomb structure consists of first manufacturing a flat honeycomb core material. A force is applied to cells of the flat honeycomb structure to deform or collapse the honeycomb cells in the

2

area in which the short angle bend is desired. This deformation of the honeycomb cells results in a honeycomb structure having a short radius bend area possessing cells with a height similar to the height of cells in the non-collapsed area.

Other methods of contouring core material consist of passing a pre-formed, flat honeycomb core material through a series of rollers that deforms the hexagonal cells and allows them to be bent in different directions. Still further methods of forming core material into a desired shape consist of beginning with a flat core material and forcing the core material against and into a die having the required contour.

All of the foregoing methodologies require the application of force to a flat honeycomb structure in order to form it into a desired shape, which may lead to undesirable stresses in the honeycomb structure. Further, the strength and stiffness of the core are sacrificed due to the fact that the honeycomb cell walls are no longer normal to the surface of the core.

Other methods generally avoid bending or folding a fully assembled honeycomb core material. Instead, these methods begin by forming flat, rectangular strips having a plurality of sections along the length of the strips, the sections being separated by fold lines. The strips are folded at the fold lines and joined together to form a desired honeycomb contour shape without additional application of force to the honeycomb core.

For example, some methods contemplate the formation of a honeycomb structure having hexagonally shaped cells wherein some cell walls possess a tapering V-shaped crimp. By placing all crimped edges on one side of the honeycomb structure, and all non-crimped edges on the opposite side of the honeycomb structure, the crimped side is made to be shorter than the non-crimped side. This facilitates variation in the radii of curvature of the honeycomb structure, which leads to a curved core material.

Other methods contemplate forming rectangular strips wherein the fold lines are placed along the length of the strips, such that the sections between the fold lines are not regularly shaped. Fold lines are placed in the strips such that when folded, the entire edges of the strips form an overall curved structure. When the folded strips are adhered together, the resulting core material has a desired contour. For example, Japanese Laid-Open Patent Publication No. 58-25531 and U.S. Pat. No. 5,270,095 disclose strips having some fold lines perpendicular to the length of the strip and other fold lines that are slanted in relation to the length of the strip. In a flat or unfolded state, the edges of the strip are straight and form a rectangle. In a folded state, the slanted fold lines create a folded strip with straight edges that form an overall curved structure determined by the angle of the slant in the fold lines. However, this process has limited utilization in that it can be used to manufacture honeycomb core having only a single shape.

What is needed is a simplified method of manufacturing contoured honeycomb structures that does not introduce undesired stresses or sacrifice strength and stiffness of the structure, and permits formation of contoured honeycomb core in a wide variety of shapes and sizes with minimal forming steps to provide manufacturing cost and time efficiencies.

SUMMARY

In one aspect of the disclosure, a ribbon configured for use in forming a honeycomb structure when the ribbon is in a folded state includes a first edge and a second edge. At least

3

one portion of the first edge is not parallel to at least one portion of the second edge when the ribbon is in an unfolded state.

In another aspect of the disclosure, a honeycomb structure comprises a first surface, a second surface, at least one ribbon, and a plurality of cells. The at least one ribbon comprises a first edge and a second edge. The first edge forms at least a portion of the first surface when the at least one ribbon is in a folded state. The second edge forms at least a portion of the second surface when the at least one ribbon is in the folded state. At least one portion of the first edge is not parallel to at least one portion of the second edge when the at least one ribbon is in an unfolded state. The plurality of cells is at least partially formed by the at least one ribbon.

In yet another aspect of the disclosure, a honeycomb structure comprises a plurality of cells, a first surface, and a second surface. The plurality of cells is configured such that at least two closed parallel cross-sections of a cell in the plurality of cells are different. The first surface and the second surface are formed by the plurality of cells.

In still yet another aspect of the disclosure, a method for forming a ribbon for use in a honeycomb structure is provided. A first edge and a second edge of the ribbon are shaped such that at least one portion of the first edge is not parallel to at least one portion of the second edge when the ribbon is in an unfolded state.

In yet another aspect of the disclosure, a method for forming a honeycomb structure comprising a plurality of cells is provided. A first edge and a second edge of at least one ribbon are shaped such that at least one portion of the first edge of the at least one ribbon is not parallel to at least one portion of the second edge of the at least one ribbon when the at least one ribbon is in an unfolded state. The plurality of cells is formed at least partially using the at least one ribbon in a folded state.

These and other features and benefits of the invention in its various aspects, as demonstrated separately or in combination by one or more of the various examples, will become apparent after the consideration of the ensuing description, the accompanying drawings, and the appended claims. The drawings are for illustrative purposes only and are not intended to limit the scope of the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

Various aspects of the disclosure will now be described with reference to the accompanying drawings, wherein:

FIG. 1 is an illustration of a manufacturing environment in the form of a block diagram in accordance with an aspect of the disclosure;

FIG. 2 is an illustration showing a perspective view of an example honeycomb core in accordance with an aspect of the disclosure;

FIG. 3 is an illustration of steps of a method of manufacturing a honeycomb core in accordance with an aspect of the disclosure;

FIG. 4 is an illustration of the steps used in a first embodiment of a method for determining the shape of cells in a honeycomb core in accordance with an aspect of the disclosure;

FIG. 5 is an illustration depicting determining the shape of cells in a honeycomb core in accordance with an aspect of the disclosure;

FIG. 6 is an illustration of the steps used in a first embodiment of a method for determining the shape of a ribbon used to make a honeycomb core in accordance with an aspect of the disclosure;

4

FIG. 7 is an illustration depicting determining the shape of a ribbon used to make a honeycomb core in accordance with an aspect of the disclosure;

FIG. 8 is an illustration depicting determining the shape of sections of a ribbon used to make a honeycomb core in accordance with an aspect of the disclosure;

FIG. 9 is an illustration of geometry consisting of the shape of a flat ribbon used to make a honeycomb core in accordance with an aspect of the disclosure;

FIG. 10 is an illustration showing a perspective view of a plurality of ribbons joined together to make a honeycomb core in accordance with an aspect of the disclosure;

FIG. 11 is an illustration of an aircraft in accordance with an aspect of the disclosure;

FIG. 12 is an illustration of a top view of a honeycomb structure in accordance with an aspect of the disclosure;

FIG. 13 is an illustration of a top view of a portion of a cell row in a plurality of cell rows in accordance with an aspect of the disclosure;

FIG. 14 is an illustration of a top view of a portion of a cell row in accordance with an aspect of the disclosure;

FIG. 15 is an illustration of a top view of a portion of a cell row in accordance with an aspect of the disclosure;

FIG. 16 is an illustration of a top view of a portion of a cell row in accordance with an aspect of the disclosure;

FIG. 17 is an illustration of a schematic representation of an exemplary honeycomb structure formed by multiple ribbons in accordance with an aspect of the disclosure;

FIG. 18 is an illustration of a schematic representation of a honeycomb structure formed by a single ribbon in accordance with an aspect of the disclosure;

FIGS. 19A and 19B is an illustration of a table of possible shapes for a honeycomb structure in accordance with an aspect of the disclosure;

FIG. 20 is an illustration of a process for forming a honeycomb structure in the form of a flowchart in accordance with an aspect of the disclosure; and

FIG. 21 is an illustration of a process for forming ribbons for use in creating a honeycomb structure in the form of a flowchart in accordance with an aspect of the disclosure.

Reference will now be made to the drawings, in which similar elements bear the same reference numerals.

DETAILED DESCRIPTION

The following disclosure describes improved methods and materials for manufacturing a curved honeycomb core having a desired geometrical shape from a plurality of ribbons with minimal forming steps and stresses, including methods for determining preferred ribbon geometries for manufacturing an at least partially curved honeycomb core having a desired shape. It will be understood by those skilled in the art that the principles of the methods and materials disclosed herein may be applied to form a wide variety of ribbon geometries and, thus, honeycomb core structures having a wide variety of geometrical shapes.

As used herein, the terms “geometry” or “geometries” or “geometrical”, when referring to ribbons means the shape and size of the ribbon, placement of fold lines in the ribbon and the structure of the ribbon edges (e.g., straight edge or curved edge), and when referring to honeycomb core, means the shape and size of the core, the shape and size of cells within the core and the shape and size of the core’s inner and outer surfaces (e.g., curved and/or planar) and the direction of the core’s axis.

For example, without limitation, the principles disclosed herein may be applied to form honeycomb cores having, e.g.,

5

curved geometrical shapes including any radial portion of (such as a “semi-cylindrical” tube having a semi-circular cross-section) or the whole of a cylinder having an arbitrary curvature. Generally, cylindrical shapes have a central axis, and outer and inner surfaces, which together define a thick-
ness. Both the thickness and the axis may vary from point to point on the cylinder. In other words, the axis of the cylindrical shape may have curvature that changes along its length and the thickness of the cylindrical shape may vary as well.

The cross-sectional shape of the cylinder, taken by a plane having a normal parallel to the axis of the cylinder, may also vary along the length of the axis, and may have varying eccentricities, radii, and other parameters. Therefore, as used herein, the terms “cylinder” or “cylindrical” are not limited to a regular cylinder having a straight axis and a constant circular cross-section, but can refer to any of a variety of tubular geometries having a varying cross-section surrounding a straight or curved axis including, for example, a curved radome, a cone shape, or other cylindrical shapes. The terms “cylinder” or “cylindrical” and “tube” or “tubular” may be used interchangeably throughout this specification. It will be appreciated that variations in the geometry, composition, and construction of such honeycomb cores can be adapted depending on their intended use in accordance with the teachings of this disclosure.

Referring now to the figures and, in particular, to FIG. 1, an illustration of a manufacturing environment in the form of a block diagram is depicted in accordance with an aspect of the disclosure. The manufacturing environment 100 depicted in FIG. 1 may be an example of one environment in which a sandwiched structure 102 may be manufactured.

As depicted, the sandwiched structure 102 may comprise a first skin 104, a second skin 106, and a core 108. The core 108 may be located between the first skin 104 and the second skin 106. In particular, the sandwiched structure 102 may be manufactured by attaching the first skin 104 and the second skin 106 to the core 108 such that the core 108 is sandwiched between the first skin 104 and the second skin 106. In one illustrative example, the sandwiched structure 102 takes the form of a sandwiched composite structure 105.

In these illustrative examples, the core 108 may be implemented using a honeycomb structure 110. As used herein, the honeycomb structure 110 comprises an array of hollow cells having thin vertical walls. In one illustrative example, these vertical walls are substantially perpendicular to the first skin 104 and the second skin 106.

For example, the honeycomb structure 110 may comprise a plurality of cells 112. In some cases, the cells 112 may be organized into a plurality of cell rows 113. Each of the cells 112 may be columnar and may have a shape selected from one of, for example, without limitation, a hexagonal shape, a rectangular shape, a square shape, an octagonal shape, a pentagonal shape, a triangular shape, a circular shape, an elliptical shape, or some other type of shape. In some cases, each of the cells 112 may have a shape that is an approximation of one of the shapes described above.

The cell rows 113 may be arranged such that adjacent rows are aligned substantially parallel to each other. Depending on the implementation, the cell rows 113 may be arranged in any orientation relative to the overall shape of the honeycomb structure 110. For example, the cell rows 113 may be oriented parallel to, perpendicular to, or at some angle relative to a longitudinal axis of the honeycomb structure 110.

In these illustrative examples, the honeycomb structure 110 is formed such that the honeycomb structure 110 has a desired three-dimensional (3D) shape 114. In one illustrative example, the desired three-dimensional shape 114 may be

6

selected from, for example, without limitation, a set of shapes 115 stored in a database 117. As used herein, a “set of” items means one or more items. In this manner, a set of shapes may be one or more shapes.

The shape selected from the database 117 may be a three-dimensional shape formed by a first surface shape 120 and a second surface shape 122. The first surface shape 120 may be, for example, an outer surface shape, while the second surface shape 122 may be, for example, an inner surface shape. In these illustrative examples, at least a portion of the first surface shape 120 is not parallel to at least a portion of the second surface shape 122. For example, without limitation, the desired three-dimensional shape 114 may be a cylindrical tube shape, a radome shape, a semi-spherical shape, a prism-type shape, a horseshoe-type shape, a donut-type shape, a curved shape, a conical shape, or some other type of shape.

The honeycomb structure 110 of the sandwiched composite structure 105 has a first surface 116 and a second surface 118. These two surfaces are discontinuous surfaces. In other words, the first surface 116 and the second surface 118 may not be solid surfaces because the cells 112 that form the honeycomb structure 110 are hollow at both ends of cells 112. The honeycomb structure 110 is formed having the desired three-dimensional shape 114 such that the first surface 116 has the first surface shape 120 and the second surface 118 has the second surface shape 122. Consequently, at least a portion of the first surface 116 of the honeycomb structure 110 is not parallel to at least a portion of the second surface 118 of the honeycomb structure 110.

In these illustrative examples, the honeycomb structure 110 is formed by a plurality of ribbons 126. These ribbons are joined together using one or more different types of joining techniques. The different types of joining techniques that may be used to join the ribbons 126 may include, but are not limited to, welding, brazing, gluing, curing, and/or other types of processes.

The ribbons 126 may be joined according to a predetermined order such that each of the ribbons 126 has a particular position and orientation in the honeycomb structure 110. In these illustrative examples, when the ribbons 126 are positioned relative to each other and joined together, the ribbons 126 create the honeycomb structure 110 having the desired three-dimensional shape 114. In particular, once the ribbons 126 are joined together to form the honeycomb structure 110, this honeycomb structure 110 may have the desired three-dimensional shape 114 without requiring additional forming operations to achieve this desired shape.

In these illustrative examples, each of the ribbons 126 is manufactured having a geometry based on the designated location for that ribbon within the honeycomb structure 110.

For example, a ribbon 128 may be configured to have a designated location 129 within the honeycomb structure 110. The designated location 129 may include both a position for the ribbon 128 relative to other ribbons in the honeycomb structure 110 and/or an orientation for the ribbon 128.

The position of the ribbon 128 relative to the other ribbons may be determined by the number of ribbons on either side of the ribbon 128 within the honeycomb structure 110. For example, each of the ribbons 126 may have an assigned position with an ordered sequence for the ribbons 126. The position of the ribbon 128 may be the assigned position of the ribbon 128 within this ordered sequence.

The orientation of the ribbon 128 may be defined with respect to the desired three-dimensional shape 114. For example, without limitation, when the desired three-dimensional shape 114 is a cylindrical tube shape, the orientation of the ribbon 128 may be described with respect to a lengthwise

center axis of the cylindrical shape. In these illustrative examples, all of the ribbons **126** are configured to have the same orientation.

The ribbon **128** has a folded state **152** within the honeycomb structure **110**. The ribbon **128** may be folded along fold lines **136** arranged generally transversely along the ribbon **128** to facilitate the change from an unfolded state **150** of the ribbon **128** into the folded state **152**. In some cases, these fold lines **136** may be imaginary fold lines or conceptual fold lines. In other cases, these fold lines **136** may be marked on the ribbon **128** using, for example, ink, color, perforations, and/or some other type of marking.

In the unfolded state **150**, the ribbon **128** is planar. In other words, the ribbon **128** is laid out flat in the unfolded state **150**. The ribbon **128** is manufactured in the unfolded state **150** with a preselected geometry based on the designated location **129** for the ribbon **128** within the honeycomb structure **110** and the way in which the ribbon **128** is to be folded.

As depicted, the ribbon **128** has a first edge **138** and a second edge **140**. The first edge **138** and the second edge **140** of the ribbon **128** are shaped such that at least one portion of the first edge **138** is not parallel to at least one portion of the second edge **140** when the ribbon **128** is in an unfolded state **150**. In particular, the first edge **138** may be configured to have a first desired contour and the second edge **140** may be configured to have a second desired contour when the ribbon is in the folded state **152**. At least one of the first desired contour and the second desired contour may not be linear along the entire corresponding edge.

In these illustrative examples, the ribbon **128** comprises a plurality of sections **130**. These sections **130** may be generally defined or separated by the fold lines **136** arranged generally transversely along the ribbon **128**.

The sections **130** of the ribbon **128** have first section edges **131** and second section edges **133**. The first section edges **131** and the second section edges **133** are shaped such that the ribbon **128** has a specific geometry when the ribbon **128** is in the unfolded state **150**. For example, a first section edge of at least one section of the sections **130** is not parallel to a second section edge of at least one other section of the sections **130** when the ribbon **128** is in the unfolded state **148**.

As one illustrative example, a section **135** has a first section edge **137** and a second section edge **139**. At least one portion of the first section edge **137** may not be parallel to at least one portion of the second section edge **139**. In some cases, at least a portion of the first section edge **137** and/or at least a portion of the second section edge **139** may not be parallel to at least a portion of another second section edge and/or at least a portion of another first section edge, respectively, of another ribbon section.

Additionally, at least one section of the sections **130** of the ribbon **128** may have a first section edge with a first radius of curvature and a second section edge with a second radius of curvature in which the first radius of curvature and the second radius of curvature are the same or different. In some illustrative examples, at least one section of the sections **130** of the ribbon **128** may have at least one section edge that has a radius of curvature that changes along the length of the section edge.

In some illustrative examples, the sections **130** of the ribbon **128** include a plurality of node sections **132** and a plurality of non-node sections **134**. In these examples, the node sections **132** and the non-node sections **134** may alternate such that no two sections of the same kind are adjacent to each other in the ribbon **128**.

As used herein, a “node section” of a ribbon, such as one of the node sections **132**, is a section of the ribbon configured to be joined with a corresponding node section of another rib-

bon. In other words, a node section of a ribbon is configured such that another ribbon may come into contact with a side of the node section and be joined to the ribbon at this side of the node section.

As used herein, a “non-node section” of a ribbon, such as one of the non-node sections **134**, may be a section of the ribbon configured such that this section does not come into contact with any section of another ribbon. In other words, a non-node section of a ribbon is configured such that both sides of the non-node section remain exposed when another ribbon is joined to the ribbon.

In one illustrative example, a first section edge and a second section edge of a node section in the node sections **132** may be at least partially linear when the ribbon **128** is in the unfolded state **150**. Further, a first section edge and a second section edge of a non-node section in the non-node sections **134** are at least partially curved and not parallel to each other when the ribbon **128** is in the unfolded state **150**.

For example, a node section in the node sections **132** may have a first section edge and a second section edge that are linear and parallel when the ribbon **128** is in the unfolded state **150**. Further, a non-node section in the non-node sections **134** may have a first section edge and a second section edge that are curved and not parallel when the ribbon **128** is in the unfolded state **150**.

In this example, the node section may be rectangular, while the non-node section may be a trapezoidal-type shape. In particular, the non-node section may be a curved trapezoidal shape.

When the ribbon **128** is folded into the folded state **152** in this illustrative example, at least portions of the first section edges of the node sections **132** may be substantially parallel to each other and at least portions of the first section edges of the non-node sections **134** may be angled and/or curved relative to the first section edges of the node sections **132**.

Further, when the ribbon **128** is in the folded state **152**, the first edge **138** and the second edge **140** of the ribbon **128** may substantially conform to the portion of the first surface shape **120** and the second surface shape **122**, respectively, corresponding to the designated location **129** for the ribbon **128** within the honeycomb structure **110**. In particular, the first edge **138** may substantially conform to a curve or another geometric feature along the first surface shape **120** and the second edge **140** may substantially conform to a curve or another geometric feature along the second surface shape **122**.

The curve along the first surface shape **120** may have one or more different radii of curvature along the length of the curve. Similarly, the curve along the second surface shape **122** may have one or more different radii of curvature along the length of the curve. In other words, the first edge **138** and/or the second edge **140** of the ribbon **128** may have one or more different radii of curvature along the lengths of these edges. The different radii of curvature may have a range between a value above zero and up to infinity. When the radius of curvature for a portion of one of the first edge **138** and the second edge **140** is infinity, the portion may be straight or linear.

In this manner, the ribbons **126** used to create the honeycomb structure **110** may be implemented in a variety of different ways. In one illustrative example, each of the ribbons **126** may be implemented in a manner similar to the ribbon **128** described above such that all of the ribbons **126** have the same geometry in the unfolded state **150**. Each of the ribbons **126** having the same geometry may allow the ribbons **126** to be manufactured more quickly and more easily as compared to when the ribbons **126** have different geometries. Further, assembly of the ribbons **126** to form the honeycomb structure

110 may be performed more quickly and easily when all of the ribbons 126 have the same geometry.

However, in some illustrative examples, a portion of the ribbons 126 may have the same geometry as the ribbon 128 described above, while another portion of the ribbons 126 may have different geometries. In other illustrative examples, each of the ribbons 126 may be manufactured having different geometries.

The ribbon 128 described above, when in the folded state 152, may be joined with at least one other ribbon in a corresponding folded state to form at least a portion of the cells 112 that make up the honeycomb structure 110. For example, when the ribbon 128 is in the folded state 152, one side of the ribbon 128 may be joined with another ribbon in the ribbons 126 in a corresponding folded state to form one of the cell rows 113. The non-node sections of these ribbons may form the walls of the cells in the cell row.

In these illustrative examples, the cells 112 may be configured such that at least two closed parallel cross-sections of at least one cell in the cells 112 are different. As used herein, a “closed cross-section” of a cell is a cross-section through the cell that has a closed boundary formed by the walls of the cell. In one illustrative example, the closed parallel cross-sections of the cell may be cross-sections that are perpendicular to a center axis through the cell. These closed parallel cross-sections may be different from each other by having different sizes, different shapes, and/or other types of differences.

For example, in some cases, at least two closed parallel cross-sections of the cell may have different perimeter lengths. A “perimeter length” of a cross-section, as used herein, is the length of the boundary of that cross-section. Further, in other cases, at least two closed parallel cross-sections of the cell may have different areas. As used herein, the “area” of a cross-section is the area within the boundary of the cross-section. In some illustrative examples, at least two parallel cross-sections of the cell that are perpendicular to a center axis through the cell may have different shapes.

Of course, in other illustrative examples, the ribbon 128 described above may be the only ribbon used to form honeycomb structure 110. For example, the ribbon 128 may form the entire honeycomb structure 110 when the ribbon 128 is in the folded state 152. The ribbon 128 may be folded along one direction, wrapped around, and then folded along the opposite direction any number of times to form the honeycomb structure 110. As the ribbon 128 is folded and wrapped, the node sections 132 of the ribbon 128 may be joined together such that the cells 112 of the honeycomb structure 110 are created.

Manufacturing a single ribbon with the necessary geometry to form the honeycomb structure 110 may be less time-consuming and/or may be easier than manufacturing multiple ribbons that need to be cut and joined together. For example, using multiple ribbons may require additional effort and time to keep track of the ribbons, especially the ribbons with different geometries, during the folding and joining of the different ribbons to form the honeycomb structure 110.

In these illustrative examples, the different ribbons 126 used to form the honeycomb structure 110 may be comprised of any number of different materials. In some cases, the ribbons 126 may all be comprised of the same type of material or a combination of materials. In other cases, different ribbons may be comprised of different types of materials and/or combinations of materials. The ribbons 126 may be comprised of, for example, without limitation, a metal, a metal alloy, a ceramic material, a plastic material, a composite material, a carbon fiber-reinforced plastic material, a nonmetallic fiber-reinforced plastic material, aluminum, titanium,

and/or other types of materials. In some cases, one or more of the ribbons 126 may be comprised of layers of the same and/or different materials.

The illustration of the manufacturing environment 100 in FIG. 1 is not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be optional. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined, divided, or combined and divided into different blocks when implemented in an illustrative embodiment.

With reference now to FIGS. 2-10, illustrations describing one manner in which honeycomb structure 110 from FIG. 1 may be implemented are depicted. In FIGS. 2-10, an example of a honeycomb structure formed by hexagonally shaped cells is described.

Turning now to FIG. 2, an illustration of a core is depicted in accordance with an aspect of the disclosure. In FIG. 2, core 200 may be an example of one implementation for core 108 in FIG. 1. The core 200 may be a honeycomb core in these illustrative examples. In other words, the core 200 may be implemented using a honeycomb structure, such as honeycomb structure 110 in FIG. 1.

For ease of description, the core 200 is shown in the shape of a regular cylinder having a straight axis 204 and a thickness 212. The core 200 comprises a series of folded ribbons 205 joined in a side-by-side manner. The ribbons 205 are shaped precisely so that when folded and joined together, they form the desired curved honeycomb geometry, including a series of abutting hexagonally shaped cells 202 extending from an outer surface of the core to an inner surface of the core and having a thickness 212. With a sufficient number of ribbons 205 joined in this fashion, any portion of a cylindrical geometry having desired curvatures may be formed.

Each of the abutting cells 202 comprises a plurality of walls, including node walls and non-node walls, and top and bottom hexagonally shaped faces corresponding to the outer and inner surfaces of the core 200, respectively. Node walls 214 are walls that provide surfaces for two adjacent ribbons 205 to be joined together, as shown in FIG. 10. Non-node walls 216 are all other walls that comprise the cells 202. As described below, the node walls 214 are tapered inward from the top face to the bottom face such that the top face has an area that is greater than the bottom face and each of the cells 202 has a tapered wedge shape. Unlike methods of making a curved honeycomb core from a flat honeycomb core, which may require stronger forces to be applied to the flat honeycomb core, the methods and materials provided herein allow the manufacture of a honeycomb core having a desired curvature without the application of strong forces and with minimal forming.

A close-up of a specific example of a ribbon geometry that may be used to form the regular cylinder honeycomb core shown in FIG. 1 can be seen in FIG. 9. The ribbon 900 is in an un-folded or flat state. Because the cylinder is regular, the geometry of the ribbon 900 is also regular—it comprises a repeating series of rectangular sections 804 followed by trapezoidal sections 802. However, it should be understood that for less regular core geometries, the geometry of the ribbon is not necessarily regular. Thus, for an irregularly shaped honeycomb core, ribbons may comprise a series of sections having shapes that are different from each other. The term “sections” as used herein refers to the discrete shapes, such as rectangle 804 and trapezoid 802, that comprise the ribbons. In the rectangular sections 804, the top and bottom edges are straight and perpendicular to the fold lines that form the side

11

edges of the sections. In the trapezoidal sections **802**, the top and bottom edges are curved to conform to or match the curvature of the inner and outer surfaces of the formed honeycomb core.

As described above, these section shapes may vary depending on the desired geometry of the honeycomb core. It should be understood that the geometry of the ribbon is defined by the shape of these sections. For example, the geometry of the ribbon **900** in FIG. **9** is defined by the fact that a rectangular section having a defined shape is joined to a trapezoidal section having a defined shape, and so forth. A consequence of this particular combination of section shapes is that the edges of the ribbon as a whole are “curved” along the length of the ribbon when the ribbon is in a flat or unfolded state. However, this curvature is not necessarily found in all ribbon geometries that may be used in accordance with the principles of this disclosure. When folded, however, the edges of the folded ribbon are straight.

In addition to being defined by the geometry of the honeycomb core **200**, the geometry of the ribbon **900** is also defined by the shape of the cells **202**. In FIG. **2**, these cells are elongated, tapered hexagonal cells. Preferably, the shape of these cells is determined, and then the geometry of the ribbons is determined based on the shape of the cells. This is described in greater detail with respect to FIGS. **4** and **5** and FIGS. **6-9** below. FIG. **9** discloses one preferred method for determining the geometry of a ribbon.

A common feature among ribbons having different geometries that are formed in accordance with the principles in this disclosure is that the edges of each of the sections of the ribbons are designed to exactly or very nearly match the shape of the portion of the honeycomb core which it forms. For the example ribbon **900** depicted in FIG. **9**, edge **818** is curved. When this ribbon **900** is folded, as shown in FIG. **8**, which depicts a close-up view of a portion of a folded ribbon embedded within a regular cylinder, edge **818** matches the curvature of the portion of the outer surface of the honeycomb core that it forms. This curvature is represented by ellipse **824**. As can be seen, edge **818** matches the curvature of this ellipse **824**, which denotes the curvature of the cylindrical surface in the direction of edge **818**. It can also be seen that edge **816**, which is not curved, but straight, matches the shape of the portion of the outer surface of the honeycomb core that it forms. Because edge **816** is parallel to the axis of the cylinder, and because the cylindrical surface is simply a straight line in that direction, edge **816**, which “matches” this straight line, is not curved. A detailed description of the methodology for determining the geometries of the ribbons, edges and sections is disclosed below.

The shapes of various objects discussed herein may be determined using geometrical principles. Some of the geometrical determinations may be made using basic mathematical principles. However, for complex shapes, while basic mathematical principles may be used, it is considered more practical to determine the shapes of such objects using numerical methods. As one of the most powerful tools for using numerical methods to determine complex geometrical shapes is 3D CAD software, some of the disclosure provided herein will make reference to operations conducted on such software. Virtually any 3D CAD software package capable of performing such operations or equivalents should be suitable to the task of making the geometrical determinations disclosed herein. One such software package is CATIA from Dassault Systèmes de Vélizy-Villacoublay, France.

With reference now to FIGS. **3-10**, illustrations for a procedure for manufacturing a honeycomb core with a desired curved geometry are described in accordance with an illus-

12

trative embodiment. The process described in FIGS. **3-10** may be an illustrative example of one manner in which a core, such as honeycomb core **200** in FIG. **2** may be formed with the desired curved geometry.

Turning now to FIG. **3**, an illustration of a general process for forming a honeycomb core in the form of a flowchart is depicted in accordance with an aspect of the disclosure. This process makes reference to various geometrical shapes that may be represented mathematically or using a computer model.

In step **300**, the shapes of outer and inner surfaces of a honeycomb core to be constructed are selected. These surfaces represent outer and inner walls of the final product that will be manufactured using the methodologies of this disclosure. A desired tubular shape is therefore provided in the form of mathematical parameterizations, or 3D CAD computer models, for an inner and outer surface of the desired tubular shape. It should be understood that this tubular shape may be any of a wide variety of curved cylindrical geometries.

It should also be understood that these inner and outer surfaces can be thought of in several ways. In particular, the inner surfaces and outer surfaces may represent approximations of the actual geometry of the honeycomb core. Further, the inner surfaces and outer surfaces may represent an “intended” overall shape of the honeycomb core. However, these surfaces may not necessarily represent the geometry of the actual finished honeycomb core product.

For example, FIG. **7** depicts inner surface **705** and outer surface **703**, which are cylindrical in shape. However, it can be seen from, e.g., FIG. **2**, that the actual shape of the honeycomb core is a composite structure comprised of a plurality of hexagonal cells, which together form a cylindrical shape. The inner and outer surfaces are thus simply analytical tools used to design a honeycomb core having a desired overall shape.

In step **302**, a ribbon orientation is selected. This is the direction along the honeycomb core at which ribbons will lie. The ribbon orientation relates to the shape of the cells of the honeycomb core as well as the geometries of the ribbons themselves. Preferably, a ribbon orientation should be selected such that the honeycomb core can be made using the smallest number of different ribbon geometries. It is desirable to use as few ribbon geometries as possible to provide cost and manufacturing time efficiencies. This can be done by determining a direction in which the cylinder has symmetry, and then selecting the ribbon orientation such that it is aligned with that symmetry. If this is optimally done, ribbons of identical geometry may be used to form the entire cylindrical core. This is described in further detail below, with respect to FIGS. **4-9**.

In step **304**, the shape, size and position of a pattern of cells that form the honeycomb core is determined. Each cell has inner and outer faces, which lie on the inner and outer surfaces of the cylindrical core, respectively. The shape of the cells may be pre-known or pre-determined. Alternatively, the shape of the cells may be determined using the procedures disclosed with reference to FIGS. **4** and **5**, below. The geometry of the ribbons to be determined is based on the determined shape of the cells.

Generally, it is beneficial for the cells **202** to be shaped and positioned such that they form a staggered series of interlocking cells **202**, as shown for example in FIG. **2**. This is typically done by choosing hexagonally shaped cells, but a wide variety of interlocking cell types are known and may be employed with the teachings of this disclosure. Any polygonal shape may be used, including shapes having curved edges. Preferably, the cells are shaped such that node-walls are generally parallel to the ribbon orientation, to facilitate connection

13

between adjacent ribbons. One example of a non-hexagonal shape can be found in the standards document for product code number AMS4177 from SAE International of Warrendale, Pa., USA. The cell shape described in that document has an irregular shape, which may be described as “sombbrero” having a wide, curved, bowl-shaped bottom portion and a narrow triangular top portion. These shapes form an interlocking pattern of cells in which the space between two bowl-shaped portions of adjacent cells is identical to the shape of the narrow triangular top portion of another cell in a staggered position, and similarly, the space between two narrow triangular top portions in adjacent cells is identical to the shape of the bowl-shaped bottom portion of another cell in a staggered position.

In step 306, the geometry of the ribbons that comprise the cylindrical honeycomb core is determined based on the pattern of cells determined in step 304. The methodology for determining the geometry of these ribbons is described in more detail with reference to FIGS. 6-9 below.

It is contemplated that both steps 304 and 306, in which geometrical shapes of physical objects are determined, may be performed using mathematical principles, computer methods or some combination of both.

In step 308, flat ribbons are cut out of a desired material to the geometry specified in step 306.

In step 310, the cut ribbons are lined up side-by-side and adjacent ribbons are joined together at the node walls. The ribbons may be pre-folded prior to being joined together. Alternatively, the ribbons may be pre-stressed along fold-lines, joined together while flat prior to folding, and subsequently expanded to a desired shape. As used herein, “pre-stressed” means that ribbons are scored or pre-bent such that when an appropriate force is applied, the ribbons bend at the fold lines. By virtue of the geometry of the ribbons, a desired core geometry is formed. Alternatively, the ribbons need not be pre-stressed. Instead, when two ribbons are joined together, the portions of the ribbons which are joined together (i.e., the node-walls) are stronger and/or stiffer than the other portions of the ribbons. When a joined stack of ribbons is expanded, the non-joined portions bend while the joined portions stay substantially rigid. The expanded stack of ribbons will thus form the desired cell shapes. The process of lining up and joining the ribbons is explained in further detail below with respect to FIG. 10.

Referring now to FIGS. 4 and 5, an exemplary method for determining the shape of a pattern of cells which comprise the honeycomb core is disclosed. It should be understood that these methods make reference to geometrical shapes that can be represented as mathematical parameterizations or 3D CAD models, and that determination of the shapes disclosed herein can be done using basic mathematical principles or numerical methods, or CAD software.

FIG. 4 is an illustration of the steps for determining cell shapes, while FIG. 5 provides a depiction of an example cylindrical core geometry which illustrates an example of performing those steps. The desired cylindrical core geometry 500 is represented in this example as a hollow cylinder, with inner surface 502 and outer surface 504, and without the hexagonal cells depicted in FIG. 2. This core geometry represents the desired overall geometry that the honeycomb core will eventually have once all the ribbons are manufactured and joined together.

In step 400, a desired geometry of a honeycomb structure to be manufactured is selected and is provided in the form of an outer surface and an inner surface of the desired shape. This geometry can be represented with a CAD model or a mathematical description of the geometry. The hollow cylin-

14

dricl geometry 500 depicted in FIG. 5 is an example of one specific desired shape. The desired geometry may include any of a wide variety of hollow tubular shapes with curvature, thickness, or cross-section variation, as described above.

The core geometry 500 depicted in FIG. 5 has an inner surface 502 and an outer surface 504. The inner surface 502 and outer surface 504 are both cylindrical but have different radii. The inner surface 502 is embedded within the outer surface 504 to form a hollow cylindrical tube with a thickness defined by the difference between the two radii. Ribbons (not depicted in this figure) used to manufacture this shape will have a height approximately equal to this thickness. This example shape is a simple hollow regular cylinder with a straight axis and constant cross-section.

The shape of each of the cells is determined by selecting a “shape” for the cells in the form of a desired two-dimensional cross-section (for example, a hexagon) and taking a projection of the selected two-dimensional cross-section onto the inner and outer surfaces of the cylinder. As described above, cells are typically formed in the shape of a hexagon, but many other shapes may also be selected.

In step 402, a desired cross-section and distance from the cross-section to the axis of the cylinder are selected. This desired two-dimensional cross-section is oriented such that the cross-section is normal to the radius of the cylinder at the center of the cross-section.

If the axis 510 of the cylinder 500 has no curvature, then it is beneficial for at least two edges in the desired two-dimensional cross-section to be approximately parallel to each other, as this provides surfaces for adjacent ribbons to be adhered together. These two edges correspond to node walls in the cells. Similarly, if the axis 510 of the cylinder 500 has curvature, it is beneficial for two edges in the desired two-dimensional cross-section to be parallel to the radius of curvature of the axis, as this facilitates connection between adjacent ribbons oriented parallel to the radius of curvature of the axis of the cylinder. Again, these two edges correspond to node walls in the cells. The orientation of these two edges corresponds to a “ribbon orientation,” which is a direction along the surface of the core in which the ribbons will lie. These two edges should be roughly aligned with the ribbon orientation, so that these edges in adjacent ribbons will be parallel to each other.

In the example shown in FIG. 5, a regular hexagon 506 is chosen as the desired two-dimensional cross-section 506, and the center 508 of the regular hexagon 506 is a desired distance X from the axis 510 of the cylinder 500.

In step 404, the two-dimensional cross-section is projected onto the outer and inner surfaces of the cylinder to form outer and inner faces of a cell, respectively. The projection may be done by drawing lines from the vertices of the cross-section to the axis of the cylinder. Preferably, the lines are drawn down to two points on the axis. To do this, the vertices of the cross-section are divided into two groups separated by a line perpendicular to axis 510 and passing through the center 508 of the cross-section 506. These two groups are on opposite sides of the center 508 of the cross-section. Lines from each vertex in the same group are drawn to the same point on the axis, as shown in FIG. 5. Preferably, one of these lines is perpendicular to the axis, while the other lines are not necessarily perpendicular. The perpendicular lines are drawn from vertices lying on a plane parallel to the ribbon orientation, and bisecting the cross-section.

In FIG. 5, lines 514 are drawn from the cross-section’s vertices 516, to the axis 510 of the cylinder 500. This results in a wedge 518 running from the cross-section 506 to the axis

15

510 of the cylinder 500, and creates an inner projection 522 and an outer projection 520 on the inner surface 502 and outer surface 504, respectively.

In step 406, the vertices of the outer and inner faces are connected by edges to form the cell. The result is a cell shape and cell position for one cell of the honeycomb structure having thickness defined by the height of the walls of the cells. In FIG. 5, the cell 512 can be seen.

In step 408, cell shapes and positions are determined for a sufficient number of cells on the entire cylindrical honeycomb structure as desired. If the cylinder is sufficiently regular in shape (e.g., has a constant cross-section, constant axis curvature or zero axis curvature), a determined cell shape can be repeated through a portion of or through the entire cylinder. In that situation, cell shapes need to only be determined once, or a limited number of times. If the cylinder is not sufficiently regular, cell shapes may be determined for each point on the cylinder as necessary.

For example, with a regular cylinder having a straight axis and a constant circular cross-section, the shape of the cells will be the same at any point on the cylinder, since the geometry of the cylinder is completely uniform.

On the other hand, with a tapered cylinder (i.e., a truncated cone or a cone shaped cylinder), the cell shape may vary from one end of the tapered cylinder to the other. However, if the tapered cylinder has radial symmetry (e.g., it has a circular cross-section decreasing in radius from one end of the cylinder to the other), then a pattern of cells can be repeated around the axis of symmetry (i.e., identical patterns of cells exist for patterns of cells lying in the direction of the length of the tapered cylinder). Any of these types of symmetries are useful in determining to what extent ribbon geometries are identical throughout the cylinder (and therefore for choosing a desired ribbon orientation). Sequences of cell shapes which are identical to each other (even though all cells within in each sequence may not have the same shape) allow the creation of identically shaped ribbons, shaped to correspond to the identical sequences of cell shapes. The ribbon orientation is preferably chosen such that the ribbons are in the same direction as the identical sequences of cell shapes.

If the axis of the cylinder is curved, then the shapes of the cells vary in a direction traveling around the axis of the cylinder. If the axis of the cylinder has a constant curvature, then a form of symmetry exists (rotated around the axis of curvature), and patterns of cells in the direction of that symmetry exist which are identical (e.g., for a torus, or a portion of a torus, identical patterns of cells exist in a direction which is parallel to the cross-section of the cylinder). Additional such symmetries may be determined and are relevant for determining appropriate ribbon geometry which is discussed in more detail below.

FIGS. 6-9 depict a method of determining the geometry of ribbons comprising honeycomb core. This method begins with step 600, by providing a representation, in mathematical terms, or in computer model form, of a honeycomb core cylinder having a defined pattern of cell shapes. This representation may either be pre-defined or may be determined using the disclosure provided above. The overall geometry of the honeycomb core, as well as the geometry of the cells are analyzed to determine the geometry of ribbons for forming the honeycomb core. The example geometry provided in FIGS. 4B-4D is a regular cylinder (straight axis, constant circular cross-section) with roughly identical hexagonal cells, but the principles disclosed herein may be applied to a wide variety of cylindrical geometries.

The computer model representation or mathematical representation of the cells in the cylinder is analyzed and

16

“divided” to form at least one linear sequence of half-cells. The term “divided” refers to a mathematical or computer operation in which a defined geometry is “cut” by a surface such as a plane, to determine the shape of a portion of that defined geometry. The direction of the divide approximately follows the direction of the ribbon orientation. More specifically, the representation of cells in the cylinder is divided by a surface which runs adjacent to node walls of adjacent cells in the direction of the ribbon orientation. This surface is shaped to follow the ribbon orientation and to be adjacent to the node walls of the cells. Further, each surface alternately divides in half, and then runs adjacent to, the cells in the honeycomb core. To obtain a linear sequence of half-cells, in step 602, at least two such surfaces are provided—these two surfaces “enclose” a sequence of half-cells having alternating orientations. These dividing surfaces are also referred to herein as “dividing walls.”

In FIG. 7, two such dividing walls 701, 702 are shown. For clarity, FIG. 7 depicts only a small portion of cells in the cylinder 700. These walls run along the cylinder in a direction parallel to the axis 710 of the cylinder 700, and have a height 706 parallel to the radius 708 of the cylinder 500. Note that in this example, the ribbon orientation is in a direction parallel to the axis 710 of the cylinder, which is why the surfaces 701, 702 run in that direction.

In step 604, a linear sequence of half-cells is determined. This sequence is the result of performing a slicing operation (with, e.g., CAD software) on a model of the core with two adjacent dividing surfaces.

In FIG. 7, between two adjacent dividing walls 701 and 702, a linear sequence of half-cells 720 is shown. This linear sequence of half-cells 720 comprises a series of half-cells in alternating orientation. Each of the half-cells has cell walls.

In step 606, the shape of each wall in the linear sequence of half-cells is determined. In FIG. 7, the linear sequence of half-cells 720 possesses walls consisting of an alternating sequence of non-node walls 712 followed by node walls 714. The shape of all cell walls within the linear sequence of half cells should be determined. The shape of the linear sequence of half-cells is equivalent to the shape of a ribbon located at the ribbon location corresponding to the space between the two adjacent dividing walls 701 and 702, and folded to form the linear sequence of half cells. The determination of this ribbon shape can be done using CAD software, or for simple geometries, by applying mathematical principles. If the geometry of the ribbon is sufficiently regular (i.e., if the ribbon comprises identical half-cells), then only a small portion of the geometry of the entire ribbon must be calculated—this portion can be repeated for the entire length of the ribbon.

In step 608, the geometry of a flat ribbon is determined based on the wall shapes from step 606. This is described in more detail with respect to FIG. 9.

In step 610, steps 602 through 608 are repeated as needed for each type of ribbon required to form the desired cylindrical geometry. In FIG. 7, which depicts a regular cylinder, only one type of ribbon geometry exists. Therefore, the geometry of the ribbon already determined may be used throughout the cylinder, and steps 602 through 606 need not be repeated.

FIG. 8 depicts a close-up of a portion of a representation of one full half-cell 720 (on the right side of the drawing) and a portion of another half-cell (on the left side of the drawing) for a honeycomb structure having a regular cylindrical geometry (constant circular cross-section, uncurved axis). Each half-cell 720 depicted in this figure has two non-node walls 802 and one node wall 804. Vertices 806, 807, 808, 809, and edges 816, 817, 818, 819 of each of the walls 802, 804 are shown.

17

Node wall **804** has a top edge **816**, a bottom edge **817**, and two side edges **820**. Non-node walls **802**, have two side edges **820**, a top edge **818** and a bottom edge **819**. The top edge **816** and bottom edge **817** of the node-walls **804** are identical in length, as are the two side edges **820**. The side edges **820** of the node walls **804** and non-node walls **802** are also identical in length and are at angle α with respect to each other. The angle α may be determined by extending a first line from vertex **809** perpendicular to the axis (not shown in this figure) and to a point on the axis, and extending a second line from vertex **813** to the same point on the axis. The angle between these two lines is equivalent to angle α .

Top edge **818** and bottom edge **819** of non-node walls **802** have a curvature that conforms to the geometry of the core cylinder **700**. Because the top edge **818** traces the outer surface **703** of the cylinder, and the bottom edge **819** traces the inner surface **705** of the cylinder, and because the outer surface **703** has a larger radius than the inner surface **705**, the top edge **818** is longer than the bottom edge **819**.

Top edge **818** is shaped like an arc section of an ellipse formed by intersecting a plane with the outer surface **703** of the cylinder **700**. The plane is parallel to the radius of the cylinder and contains the two vertices **807**, **806** of top edge **818**. Similarly, the bottom edge **819** is shaped as an arc section of an ellipse formed by intersecting a plane with the inner surface of the cylinder. The plane is parallel to the radius of the cylinder and contains the two vertices **809**, **808** of bottom edge **819**. If the cells are shaped approximately as a regular hexagon, these planes may be approximated as planes parallel to the radius and rotated by approximately 120 degrees with respect to the axis. In FIG. 8, these planes are not shown directly—only the intersection of the planes with the inner surface **705** and outer surface **703** of the cylinder respectively can be seen. These intersections are inner elliptical arc **822** and outer elliptical arc **824** which both follow the surface of the cylinder **700**.

The calculations for determining the shape of edges **818-819** may be simplified by approximating edges **818-819** as arcs of a circle having a radius equivalent to the radius of the cylindrical surface on which the curved edges **818-819** lie. Further, the arc-length of the curved top or bottom edges may be approximated as $\Theta \cdot R$, where Θ is equal to the angle traversed by the curved edges **818-819**. These approximations are fairly suitable if the size of the cells is much smaller than the radius of the cylinder, but becomes less accurate as the size of the cell becomes closer to the size of the cylinder.

Although the ribbons are described and depicted above as being identical for all locations throughout the cylindrical core geometry, varying core geometries may require different ribbon geometries. For manufacturing purposes, it is beneficial to have the smallest number of ribbon geometries.

For certain cylindrical shapes, only one ribbon geometry needs to be made. For others, a small number of ribbon geometries needs to be made. For the most complex cylindrical geometries, each ribbon would have to be customized for its location.

The presence of radial symmetry in a cylindrical geometry allows the use of identical ribbons running in a direction parallel to that symmetry. For example, a regular cylinder has radial symmetry around its axis, meaning that identical ribbons may be used if the ribbons run in the direction perpendicular to the axis of the cylinder. A tapered cylinder or a cylinder with a bulge in the middle similarly has radial symmetry around its axis, so identical ribbons may be used if the ribbons run in the directions established by lines of intersection between the surfaces of the tapered cylinder and planes containing the longitudinal axis of the cylinder. Further, with

18

a torus, which is a “tube” which is wrapped around a major axis having a constant curvature, identical ribbons may be used if they are positioned such that they are parallel to the major radius of the torus, i.e., wrapped around the “tube” in a direction that is parallel to the major radius of the torus. In other words, identical patterns of cells exist for patterns of cells which are wrapped around the “tube” of the torus in a direction which is parallel to the major radius of the torus. This is because a torus is a structure with radial symmetry around a major axis—this major axis is the axis around which the “tube” of the torus is wrapped.

Although some cylinder geometries may not have any of these characteristics along their entire length, some cylinder geometries may nevertheless be broken down into sections, each of which have these characteristics (for example, multiple sections of a torus attached at their ends and rotated with respect to each other, or a torus section followed by a tapered straight cylindrical section). For such cylinders, each section may be made of identical ribbons.

Further, for any desired geometry which does not exactly match one of the “ideal” shapes having characteristics described above (such as symmetry), but almost matches such an ideal shape, an ideal shape may be manufactured using the above-described methodologies and then formed (e.g., the shape of the cylinder can be changed through the application of force) into the desired non-ideal shape. Although some forming would be required in this situation, the forming would be minimal in comparison with forming a shape from flat core material.

As shown in FIG. 9, once the shapes of all of the edges, and thus the walls of the half-cells, are determined, the shape of a flat, non-folded ribbon **900** can be determined. The ribbon geometry depicted in FIG. 7 is appropriate for forming a regular cylinder having a constant circular cross-section and a straight axis. The shape of the non-folded ribbon **900** is a flat shape that comprises a succession of sections separated by fold lines, each section having a shape equivalent to a wall of each half-cell in the linear sequence of half-cells **720**.

The sections have the same order and shape as the walls in the linear sequence **720**. The shape of the edges of the sections is also the same as the shape of the corresponding edges of the walls. Thus, the first section **804** has the same shape as node wall **804**, the second section **802** has the same shape as non-node wall **802**, and so on. Further, the order of the sections in the flat ribbon **900** is the same as the order of the cell walls shown in FIGS. 7 and 8.

The flat ribbon **900** shown in FIG. 9 is curved along its length. This curvature is not necessarily a smooth curve, but is formed by the alternating straight-curved-straight edges of the rectangular sections **802** and trapezoidal sections **804**, and also due to the fact that all of the short edges of the trapezoidal sections **804** are pointed in the same direction. In addition to the specific ribbon geometry shown in FIG. 9, curvature along the length of the flat ribbon may also be present with ribbon geometries cut to form other cylinder geometries. For every such cylindrical geometry, the curvature of curved flat ribbons that form the cylinder will be due to a combination of non-rectangular section shapes and curved section edges.

When the ribbon **900** shown in FIG. 9 is folded, the ribbon's edges become straight along the length of the ribbon as shown in FIG. 10. Some curvature exists in a direction corresponding to the curvature of the cylinder being formed. For ribbons used to form other cylinder geometries, such ribbons may not be straight along their lengths when folded. For example, for ribbons used to form a cylinder having a curved axis (and therefore an outer surface that is curved in the direction parallel to the direction of the axis), the correspond-

19

ing folded ribbon may be curved along its length, to match the curved surface of the cylinder.

When the flat ribbon shape **900** is determined, a physical ribbon can be cut out of a base material such as metal or paper by conventional methods such as a stamp and press apparatus. This physical ribbon will then be folded to match the shape of the cells in the cylindrical core.

The edges **820** that separate the sections in the ribbon represent lines at which folds or bends will be made and are referred to herein as “fold lines.” The flat ribbons are folded to form contoured ribbons with troughs and ridges that correspond to the linear sequence of half cells. The ribbons should be folded to angles such that the ribbons form the cells.

For the cell shape depicted in FIG. **4C**, the direction of the fold is decided by which type of wall, node **804** or non-node **802**, the fold lines **820** surround. If two fold lines **820** surround a node wall **804**, then the folds made at both of those fold lines should be made in the same direction as each other. If two fold lines surround a non-node wall **802**, then the folds made at both of these fold lines should be made in a direction opposite to each other. In this way, a repeating pattern of two folds in one direction followed by two folds in the opposite direction is made, and a series of semi-hexagonal half-cells is formed. The angle of the folds is determined by the shape of the half cells. For regular hexagons, the folds are made at approximately 120 degrees.

As shown in FIG. **10**, the ribbons **900**, once cut and folded, are joined together to form a linear series of hexagonal cells that comprise the cylindrical core. The ribbons should be joined together at their node walls **804**. Ribbons are added in this manner until a number of ribbons required for the desired core geometry have been bound together.

If the ribbons were pre-folded, the cylindrical core is completed. Alternatively, if the ribbons were simply pre-stressed, then when it is desired to assemble the full structure, the ribbons may be pulled apart such that the structure is expanded and the ribbons are formed into the final desired structure. The expanded assembly of ribbons may be cured or otherwise solidified into the appropriate geometry. The teachings of this disclosure can be used to make a curved honeycomb core in a wide variety of geometries while requiring minimal forming.

With reference now to FIG. **11**, an illustration of an aircraft is depicted in accordance with an aspect of the disclosure. In this illustrative example, the aircraft **1100** has a wing **1102** and another wing **1104** attached to a fuselage **1106**. The aircraft **1100** may include an engine **1108** attached to the wing **1102** and another engine **1110** attached to the other wing **1104**. The fuselage **1106** may have a tail section **1112**. A horizontal stabilizer **1114**, another horizontal stabilizer **1116**, and a vertical stabilizer **1118** may be attached to the tail section **1112** of the fuselage **1106**.

The fuselage **1106** may be comprised of a composite structure having a cylindrical shape to form the cylindrical shape **1119** of the fuselage **1106**. An exposed portion **1120** of the fuselage **1106** is seen with a skin (not shown) of this composite structure removed. A honeycomb structure **1122** is seen within this exposed portion **1120**. The honeycomb structure **1122** is the core of the composite structure forming the fuselage **1106**.

Additionally, an exposed portion **1124** of a fairing **1130** attached to the fuselage **1106** is seen with a skin (not shown) of this composite structure removed. A honeycomb structure **1126** is seen within this exposed portion **1124**. The honeycomb structure **1126** is the core of the composite structure that forms the fairing **1130** and has a conical shape **1128**.

20

An exposed portion **1132** of a nose section **1138** of the fuselage **1106** is seen with a skin (not shown) of this composite structure removed. A honeycomb structure **1134** is seen within this exposed portion **1132**. The honeycomb structure **1134** is the core of the composite structure that forms the nose section **1138** and has a conical shape **1136**.

Further, an exposed portion **1140** of the wing **1104** is seen with a skin (not shown) of this composite structure removed. A honeycomb structure **1142** is seen within this exposed portion **1140**. The honeycomb structure **1142** is the core of the composite structure that forms the wing **1104** and has a curved shape **1144**.

Further, an exposed portion **1146** of the wing **1102** of the fuselage **1106** is seen with a skin (not shown) of this composite structure removed. A honeycomb structure **1148** is seen within this exposed portion **1146**. The honeycomb structure **1148** is the core of the composite structure that forms the wing **1102** and has a curved shape **1150**.

Still further, an exposed portion **1152** of the tail section **1112** of the fuselage **1106** is seen with a skin (not shown) of this composite structure removed. A honeycomb structure **1154** is seen within this exposed portion **1152**. The honeycomb structure **1154** is the core of the composite structure that forms the tail section **1112** and has a conical shape **1156**.

An exposed portion **1158** of the vertical stabilizer **1118** of the fuselage **1106** is seen with a skin (not shown) of this composite structure removed. A honeycomb structure **1160** is seen within this exposed portion **1158**. The honeycomb structure **1160** is the core of the composite structure that forms the vertical stabilizer **1118** and has a curved shape **1162**.

Additionally, an exposed portion **1164** of the nacelle **1166** of the engine **1110** is seen with a skin (not shown) of this composite structure removed. A honeycomb structure **1168** is seen within this exposed portion **1164**. The honeycomb structure **1168** is the core of the composite structure that forms the nacelle **1166** and has a curved shape **1170**.

In this illustrative example, honeycomb structures **1122**, **1126**, **1134**, **1142**, **1154**, and **1160** may be example of implementations for the honeycomb structure **110** depicted in FIG. **1**. As depicted, honeycomb structures may be used in a variety of different ways to form a variety of different structures having different types of curved shapes.

With reference now to FIG. **12**, an illustration of a top view of the honeycomb structure **1122** from FIG. **11** is depicted in accordance with an aspect of the disclosure. As depicted, the honeycomb structure **1122** is comprised of cells **1200** organized into cell rows **1202**.

The cell rows **1202** comprising the cells **1200** may be an example of one implementation for the cell rows **113** comprising cells **112** in FIG. **1**. As depicted, the cells rows **1202** are aligned parallel to an axis **1204**. In this illustrative example, the honeycomb structure **1122** has a curved shape **1206**. The curved shape **1206** may be curved about the axis **1204**.

Turning now to FIG. **13**, an illustration of a top view of a portion of a cell row in the cell rows **1202** in FIG. **12** is depicted in accordance with an aspect of the disclosure. In this illustrative example, a portion of a cell row **1300** is depicted. The cell row **1300** may be one of the cell rows **1202** in FIG. **12**.

In this illustrative example, the cell row **1300** is formed by a first ribbon **1302** and a second ribbon **1304** joined together. The first ribbon **1302** and the second ribbon **1304** may be in a folded state **1306** and a corresponding folded state **1308**, respectively. The first ribbon **1302** and the second ribbon **1304** may be joined together to form cells **1303** and **1305** in the cell row **1300**.

21

As depicted, the first ribbon **1302** comprises node sections **1310**, **1312**, **1314**, **1316**, and **1318** and non-node sections **1320**, **1322**, **1324**, and **1326**. The second ribbon **1304** may comprise node sections **1328**, **1330**, **1332**, **1334**, and **1336** and non-node sections **1338**, **1340**, **1342**, and **1344**. The node sections **1310**, **1314**, and **1318** of the first ribbon **1302** and the node sections **1328**, **1332**, and **1336** of the second ribbon **1304** may be joined together using, for example, without limitation, welding brazing, soldering, co-curing, co-bonding, adhesive bonding, and/or some other type of joining technique to form the portion of the cell row **1300** depicted in FIG. **13**.

In this illustrative example, the cells **1303** and **1305** have hexagonal shapes. However, in other illustrative examples, the cells in a honeycomb structure may have other types of shapes. Illustrations of cell rows having cells with shapes other than hexagonal shapes are depicted in FIGS. **14-16** below.

Turning now to FIG. **14**, an illustration of a top view of a portion of a cell row is depicted in accordance with an aspect of the disclosure. A portion of a cell row **1400** is depicted in FIG. **14**. The cell row **1400** may include cells **1403** and **1405**. The cells **1403** and **1405** may have hour-glass type shapes in this illustrative example.

As depicted, the cell row **1400** may be formed by a first ribbon **1402** and a second ribbon **1404**. The first ribbon **1402** may comprise node sections **1406** and non-node sections **1408**. The node sections **1406** and the non-node sections **1408** may alternate along the first ribbon **1402**. The second ribbon **1404** may comprise node sections **1410** and non-node sections **1412**. The node sections **1410** and the non-node sections **1412** may alternate along the second ribbon **1404**.

Turning now to FIG. **15**, an illustration of a top view of a portion of a cell row is depicted in accordance with an aspect of the disclosure. A portion of a cell row **1500** is depicted in FIG. **15**. The cell row **1500** may include cells **1503** and **1505**. These cells **1503** and **1505** may have rectangular shapes in this illustrative example.

As depicted, the cell row **1500** may be formed by a first ribbon **1502** and a second ribbon **1504**. The first ribbon **1502** may comprise node sections **1506** and non-node sections **1508**. The node sections **1506** and the non-node sections **1508** may alternate along the first ribbon **1502**. The second ribbon **1504** may comprise node sections **1510** and non-node sections **1512**. The node sections **1510** and the non-node sections **1512** may alternate along the second ribbon **1504**.

Turning now to FIG. **16**, an illustration of a top view of a portion of a cell row is depicted in accordance with an aspect of the disclosure. A portion of a cell row **1600** is depicted in FIG. **16**. The cell row **1600** may include cells **1603** and **1605**. These cells **1603** and **1605** may have walnut-type shapes in this illustrative example.

As depicted, the cell row **1600** may be formed by a first ribbon **1602** and a second ribbon **1604**. The first ribbon **1602** may comprise node sections **1606** and non-node sections **1608**. The node sections **1606** and the non-node sections **1608** may alternate along the first ribbon **1602**. The second ribbon **1604** may comprise node sections **1610** and non-node sections **1612**. The node sections **1610** and the non-node sections **1612** may alternate along the second ribbon **1604**.

The illustrations in FIG. **2-16** are not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be optional.

The different components shown in FIGS. **2-16** may be illustrative examples of how components shown in block

22

form in FIG. **1** can be implemented as physical structures. Further, some of the components shown in FIGS. **2-16** may be combined with components illustrated in FIG. **1**, used with components illustrated in FIG. **1**, or both.

With reference now to FIG. **17**, an illustration of a schematic representation of an exemplary honeycomb structure formed by multiple discrete ribbons is depicted in accordance with an aspect of the disclosure. In FIG. **17**, a schematic representation of a honeycomb structure **1700** is depicted with the thickness of the honeycomb structure **1700** omitted for clarity. In particular, an outer surface shape **1701** of the honeycomb structure **1700** is represented in FIG. **17**.

The honeycomb structure **1700** is formed by discrete ribbons **1702** that are schematically shown in representational form. The ribbons **1702** are aligned parallel to each other. Although the ribbons **1702** may be joined together at node sections, these details are not shown in FIG. **17** to illustrate the discrete nature of the ribbons **1702** more clearly.

Turning now to FIG. **18**, an illustration of a schematic representation of a honeycomb structure formed by a single continuous ribbon is depicted in accordance with an illustrative embodiment. In this illustrative example, a schematic representation of a honeycomb structure **1800** is depicted with the thickness of the honeycomb structure **1800** omitted for clarity. In particular, an outer surface shape **1801** of the honeycomb structure **1800** is represented in FIG. **18**.

The honeycomb structure **1800** is formed by a single continuous ribbon **1802** that is schematically shown in representational form. This ribbon **1802** may wrap around (i.e., change direction or zigzag) multiple times, such that different portions of the ribbon **1802** are aligned parallel to each other.

Although these different portions of the ribbon **1802** may be joined together at node sections of the ribbon **1802**, such details were omitted in FIG. **18** to illustrate the continuous nature of the ribbon **1802** more clearly. Those skilled in the art will appreciate that a hybrid discrete/continuous ribbon architecture may be utilized, wherein a plurality of continuous ribbons, each having at least one directional change or zigzag therein, may be used to form an exemplary honeycomb structure.

Turning now to FIG. **19**, an illustration of a table of possible shapes for a honeycomb structure is depicted in accordance with an aspect of the disclosure. In FIG. **19**, a table **1900** depicting a set of shapes **1902** is depicted. Each shape in this set of shapes **1902** is a three-dimensional shape. In this manner, any one of this set of shapes **1902** may be used to implement the desired three-dimensional shape **114** described in FIG. **1**.

The set of shapes **1902** includes a first shape **1904**, a second shape **1906**, a third shape **1908**, a fourth shape **1910**, a fifth shape **1912**, a sixth shape **1914**, a seventh shape **1916**, an eighth shape **1918**, a ninth shape **1920**, a tenth shape **1922**, an eleventh shape **1923**, a twelfth shape **1925**, a thirteenth shape **1927**, a fourteenth shape **1929**, a fifteenth shape **1931**, and a sixteenth shape **1933**. Each of these shapes may be formed by two surface shapes.

As depicted, the first shape **1904** is a cylindrical tube shape formed by a first surface shape **1924** and a second surface shape **1926**. The second shape **1906** is a cylindrical tube shape formed by a first surface shape **1928** and a second surface shape **1930**. The third shape **1908** is a cylindrical tube shape formed by a first surface shape **1932** and a second surface shape **1934**.

The fourth shape **1910** is a bottle-type shape formed by a first surface shape **1936** and a second surface shape **1938**. The fifth shape **1912** is a dome-topped shape formed by a first surface shape **1940** and a second surface shape **1942**.

23

The sixth shape **1914** is an irregular cylindrical tube shape formed by a first surface shape **1944** and a second surface shape **1946**. The seventh shape **1916** is an octagonal prism-type shape formed by a first surface shape **1948** and a second surface shape **1950**. The eighth shape **1918** is an irregular cylindrical tube shape formed by a first surface shape **1952** and a second surface shape **1954**. The ninth shape **1920** is another irregular cylindrical tube shape formed by a first surface shape **1956** and a second surface shape **1958**. The tenth shape **1922** is a deformed cylindrical shape formed by a first surface shape **1960** and a second surface shape **1962**.

The eleventh shape **1923** is a curved shape formed by a first surface shape **1964** and a second surface shape **1966**. The twelfth shape **1925** is a curved shape formed by a first surface shape **1968** and a second surface shape **1970**. The thirteenth shape **1927** is another curved shape formed by a first surface shape **1972** and a second surface shape **1974**. The fourteenth shape **1929** is a shape comprising an irregular curved shape formed by a first surface shape **1976** and a second surface shape **1978**.

The fifteenth shape **1931** is a shape comprising a curved portion and a flat portion formed by a first surface shape **1980** and a second surface shape **1982**. The sixteenth shape **1933** is a shape comprising a curved portion and a flat portion formed by a first surface shape **1984** and a second surface shape **1986**.

Each of the first surface shapes and each of the second surface shapes described above may be examples of implementations for the first surface shape **120** and the second surface shape **122**, respectively, described in FIG. 1. In this manner, honeycomb structure **110** in FIG. 1 may be formed in a number of different ways. Those skilled in the art will appreciate that the above-described shapes are merely exemplary and that the shape of the honeycomb structure may be any other shape and/or combination of the above shapes not specifically described herein.

Each of the ribbons **126** described in FIG. 1 may be formed such that the first edge and the second edge of the ribbons substantially conform to the first surface shape and the second surface shape, respectively, of the desired three-dimensional shape selected from the set of shapes **1902** when the ribbons are in a folded state. Depending on the desired three-dimensional shape, each of the ribbons **126** may have a same or different shape when folded compared to the other ribbons.

Turning now to FIG. 20, an illustration of a process for forming a honeycomb structure in the form of a flowchart is depicted in accordance with an aspect of the disclosure. The process illustrated in FIG. 20 may be implemented to form, for example, without limitation the honeycomb structure **110** in FIG. 1.

The process may begin by selecting a desired three-dimensional shape from a set of shapes for the honeycomb structure (operation **2000**). The desired three-dimensional shape may comprise a first surface shape and a second surface shape.

The process then forms a plurality of ribbons for use in creating the honeycomb structure based on the desired three-dimensional shape (operation **2002**). Thereafter, each of the ribbons is folded along pre-identified fold lines on each of the ribbons to change an unfolded state of each of the ribbons into the folded state (operation **2004**).

Next, the ribbons are joined together with each of the ribbons in the folded state to form the honeycomb structure having the desired three-dimensional shape (operation **2006**), with the process terminating thereafter. In particular, at least one portion of a first surface of the honeycomb structure may not be parallel to at least one portion of a second surface of the honeycomb structure.

24

Turning now to FIG. 21, an illustration of a process for forming ribbons for use in creating a honeycomb structure in the form of a flowchart is depicted in accordance with an aspect of the disclosure. The process illustrated in FIG. 21 may be used to implement operation **2002** in FIG. 20.

The process begins by selecting a ribbon for shaping (operation **2100**). A first edge and a second edge of the selected ribbon are then shaped such that at least one portion of the first edge is not parallel to at least one portion of the second edge (operation **2102**). Thereafter, the process determines whether any additional ribbons still need to be shaped (operation **2104**). If one or more additional ribbons still need to be shaped, the process returns to operation **2100** as described above. Otherwise, the process terminates.

The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatus and methods in an illustrative embodiment. In this regard, each block in the flowcharts or block diagrams may represent a module, segment, function, and/or a portion of an operation or step.

In some alternative implementations of an illustrative embodiment, the function or functions noted in the blocks may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be executed substantially concurrently, or the blocks may sometimes be performed in the reverse order, depending upon the functionality involved. Also, other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram.

Thus, the different illustrative embodiments provide a method and apparatus for forming a honeycomb structure having a first surface and a second surface in which at least one portion of the first surface is not parallel to at least one portion of the second surface. In one illustrative embodiment, a honeycomb structure comprises a first surface, a second surface, at least one ribbon, and a plurality of cells. The at least one ribbon comprises a first edge and a second edge. The first edge forms at least a portion of the first surface when the at least one ribbon is in a folded state. The second edge forms at least a portion of the second surface when the at least one ribbon is in the folded state. At least one portion of the first edge is not parallel to at least one portion of the second edge when the at least one ribbon is in an unfolded state. The plurality of cells is at least partially formed by the at least one ribbon.

While the disclosure has been described with reference to various embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the disclosure. In addition, many modifications may be made to adapt a particular situation to the teachings of the disclosure without departing from the essential scope thereof. Therefore it is intended that the disclosure not be limited to the particular embodiment disclosed herein contemplated for carrying out the methods of this disclosure, but that the disclosure will include all embodiments falling within the scope of the appended claims.

What is claimed is:

1. A non-planar honeycomb structure comprising:
 - a first surface;
 - a second surface opposite the first surface;
 - at least one ribbon comprising side edges along which the at least one ribbon is folded, the side edges partially defining sections of the at least one ribbon, wherein at least one of the side edges of the at least one ribbon is not

25

substantially parallel to another one of the side edges of the at least one ribbon, the sections comprising:

first section edges forming at least a portion of the first surface of the non-planar honeycomb structure, wherein the first section edges of at least two adjacent sections are not collinear when the at least one ribbon is unfolded flat; and

second section edges forming at least a portion of the second surface of the non-planar honeycomb structure, wherein the second section edges of the at least two adjacent sections are not collinear when the at least one ribbon is unfolded flat; and

cells formed by folding the at least one ribbon along the side edges.

2. The non-planar honeycomb structure of claim 1, wherein the first surface of the non-planar honeycomb structure has a first radius of curvature and at the second surface of the non-planar honeycomb structure has a second radius of curvature and wherein the first radius of curvature and the second radius of curvature are different.

3. The non-planar honeycomb structure of claim 1, wherein the at least one ribbon further comprises:

a plurality of node sections; and

a plurality of non-node sections, wherein the plurality of node sections and the plurality of non-node sections are configured to alternate along the at least one ribbon such that no one node section in the plurality of node sections is adjacent to another node section in the plurality of node sections and no one non-node section in the plurality of non-node sections is adjacent to another non-node section in the plurality of non-node sections.

4. The non-planar honeycomb structure of claim 3, wherein the sections further comprise alternating rectangular node sections and acute trapezoidal non-node sections.

5. The non-planar honeycomb structure of claim 4, wherein the cells are further formed by adhering the rectangular node sections of the at least one ribbon to other rectangular node sections, but not adhering the trapezoidal non-node sections.

6. The non-planar honeycomb structure of claim 5, wherein adhering the rectangular node sections comprises adhering the rectangular node sections by a joining technique selected from the group consisting of welding, brazing, gluing, curing, and combinations thereof.

7. The non-planar honeycomb structure of claim 3, wherein the sections further comprise alternating rectangular node sections and non-node sections, wherein at least a portion of at least one of the first section edges and the second section edges is curved when the at least one ribbon is in an unfolded state.

8. The non-planar honeycomb structure of claim 7, wherein the cells are further formed by adhering the rectangular node sections of the at least one ribbon to other rectangular node sections, but not adhering the non-node sections.

26

9. The non-planar honeycomb structure of claim 1, wherein each of the cells of the non-planar honeycomb structure is not deformed.

10. The non-planar honeycomb structure of claim 1, wherein the cells formed by folding the at least one ribbon along the side edges comprises an array of hollow cells having substantially vertical walls.

11. The non-planar honeycomb structure of claim 10, further comprising:

a first skin attached to the first surface; and

a second skin attached to the second surface.

12. The non-planar honeycomb structure of claim 11, wherein the substantially vertical walls are substantially perpendicular to the first skin and the second skin.

13. The non-planar honeycomb structure of claim 1, wherein each of the cells has a shape selected from the group consisting of a hexagonal shape, a rectangular shape, a square shape, an octagonal shape, a pentagonal shape, a triangular shape, a circular shape, an elliptical shape, and combinations thereof.

14. The non-planar honeycomb structure of claim 1, the non-planar honeycomb structure further comprising a longitudinal axis of the honeycomb structure, wherein each of the cells is oriented relative to the longitudinal axis of the honeycomb structure.

15. The non-planar honeycomb structure of claim 14, wherein each of the cells is oriented parallel to the longitudinal axis of the honeycomb structure, perpendicular to the longitudinal axis of the honeycomb structure, or at some angle relative to the longitudinal axis of the honeycomb structure.

16. The non-planar honeycomb structure of claim 1, wherein the honeycomb structure has a desired three-dimensional shape.

17. The non-planar honeycomb structure of claim 1, wherein the desired three-dimensional shape is selected from the group consisting of a cylindrical tube shape, a radome shape, a semi-spherical shape, a prism shape, a horseshoe shape, a donut shape, a curved shape, a conical shape, and combinations thereof.

18. The non-planar honeycomb structure of claim 1, wherein the at least one ribbon further comprises a plurality of ribbons.

19. The non-planar honeycomb structure of claim 18, wherein each of the plurality of ribbons has an assigned position within an ordered sequence for the plurality of ribbons.

20. The non-planar honeycomb structure of claim 19, wherein a desired three-dimensional shape is formed for the honeycomb structure by assembling the plurality of ribbons according to the ordered sequence.

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